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THE EFFICIENT BURNING OF FUEL IN HIGH-SPEED OIL ENGINES WITH PARTICULAR REFERENCE TO A CLEAN EXHAUST.*

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Synopsis.

The paper deals with the measures taken by a large passenger-transport undertaking to ensure efficient combustion of the fuel used by its fleet of oil-engined vehicles. The incentive is a dual one—viz., that of retaining the goodwill of the travelling public, and at the same time achieving an economy in fuel consumption. Incomplete combustion is visibly evidenced by exhaust smoke, four types of which are recognized; a fifth is attributable to excessive consumption of lubricating oil. The prime necessity for efficient combustion is an engine of satisfactory design using a fuel of suitable ignition quality. The combination will not show the desired result, however, without due attention being paid to cleanliness of the fuel and to careful maintenance of engine and accessories. The precautions taken in respect of the former, and the special methods employed for maintaining fuel-pumps and injectors in particular, are described in some detail. A brief account is also given of endeavours to apply exhaust-gas-analysis methods to combustion control in oil engines.

Introduction.

In the early days of the development of high-speed oil engines in this country some anxiety was felt as to whether progress might not be retarded by reason of a tendency to produce exhaust smoke, and in certain localities oil-engined vehicles were the subject of adverse public comment. Even to-day it is possible to encounter vehicles—almost without exception, it should be said, of the heavy-goods type—the exhaust smoke of which may be fairly described as a public nuisance. This is quite inexcusable, and it is the purpose of this contribution to describe the measures taken by the London Passenger Transport Board to ensure that no such trouble should arise in respect of its oil-engined fleet, the size of which has been steadily increasing throughout the past six years. The problem is one of efficient combustion of the fuel, and could be discussed at length from the viewpoint of either quality of fuel or engine design, or both. These aspects will, however, only be touched upon lightly on the present occasion. At any given moment the characteristics of both engine and fuel used may be regarded as constants, and methods of maintenance must be so adapted as to obtain the best possible results in all circumstances.

The incentive to the efficient utilization of fuel is, of course, twofold: firstly, to retain the goodwill of the travelling public, and secondly, to reduce operating expenses. It may be thought that these two aims have been placed in the wrong order, but in justification it can be stated that in every step in the replacement of petrol engines by high-speed oil engines, it has been the Board's first consideration to make sure that public complaints in respect of smell or smoke shall not arise. So successful has this policy been that as the proportion of oil engines has increased, the number of complaints of "fumes" has substantially decreased.

* Paper presented for discussion at the Morning Session (A), 24th May, at the Summer Meeting of the Institute of Petroleum held in Birmingham, 22–24th May, 1939.

† London Passenger Transport Board.

That, for any given engine, elimination of "fumes" and economy in fuel consumption go hand in hand was demonstrated many years ago, when rigid standardization of carburettor settings was established in respect of petrol engines. Prior to that time carburettors were adjusted by the garages to suit local conditions, and this latitude resulted in a tendency for engine defects to be covered up by the use of larger jets, leading thus to wastage of fuel accompanied by an unpleasant exhaust odour. While a case might be argued in favour of individual "tuning," experience has abundantly shown that for a large fleet of vehicles standardization of all the factors concerned in combustion is the proper course. It was natural, therefore, that similar measures should be taken when petrol engines came to be replaced by oil engines.

Exhaust Smoke.

With a petrol engine, incomplete combustion is chiefly evidenced by the presence of carbon monoxide in the exhaust gases, although any obnoxious or irritating odour is, of course, attributable to other partly oxidized products also present, usually in very small amounts. With the high-speed oil engine the carbon-monoxide problem may be said to be practically non-existent; occasionally 0·2 per cent. of this gas may be found in the exhaust products, and very rarely up to 0·4 per cent. Incomplete combustion can, however, occur, and is visibly indicated by a smoky exhaust. Five types of exhaust smoke may be recognized, four being associated with incomplete combustion of the fuel, whilst the fifth is due to excessive consumption of lubricating oil. A dense greyish-white smoke is momentarily produced in the case of indirect-injection engines when starting from cold. The exhaust will present a blackish haze, more or less dense, if the injectors are in poor condition, the direct-injection engine being the more sensitive in this respect. With both types of engines continuous heavy black smoke will be emitted if the setting of the fuel-pump is such as to permit an excess of fuel being injected; the excess-injection point or "smoke limit" is more definite in the case of the indirect-injection engine. The fourth type of smoke attributable to incomplete combustion is really a special case of the third, and may appear as a black puff when the vehicle is taking off from a point. It is due to momentary over-injection, and can be eliminated by correct adjustment of the low-speed injection-stop on the fuel-pump. Excessive consumption of lubricating oil results in the production of a continuous grey smoke, and to avoid any possibility of complaints arising from this cause, it is the Board's practice to keep individual records of lubricating-oil consumption, so that engines may be removed for overhaul before the smoke-point is reached. In respect of odour of the exhaust products, it can fairly be claimed that in the absence of smoke, the oil engine is no more noticeable than the petrol engine, except perhaps on the first occasion on which it is encountered, when the qualitative difference between the respective odours might be detected.

Cleanliness of Fuel.

A fuel of poor ignition quality will inevitably lead to inefficient combustion, perhaps accompanied by exhaust smoke, and the trouble will persist

despite careful maintenance of engine and accessories. A satisfactory fuel also will give trouble if it is not clean, since particles of adventitious matter will cause scoring of the fuel-pump plungers and promote blocking of pintle-holes and accumulation of carbon on injectors. In the very early days of oil-engine development this was one of the factors which had to be contended with, and we have record of an engine the power output of which was found to have decreased by over 20 per cent., due to scoring of fuel-pump plungers. A residual oil, which was in use for a short time, led to considerable accumulation of sludge in the storage-tanks. Even when oil engines were in more common use, it was the suppliers' practice to blend a little fuel-oil with the distillate fuel. They can now justifiably claim, however, that any contamination of the fuel is derived from the users' storage- or service-tanks. Certain operators pass the fuel through a centrifuge immediately before filling service-tanks, although the Board has not considered it necessary to go to this length. Adequate precautions are, however, taken to ensure that the fuel reaches the fuel-pump in as clean a condition as is possible. A sample of fuel taken from the supplier's tank-wagon is forwarded to the laboratory from each garage weekly, and, in addition to inspection for water and dirt, it is subjected to routine tests to establish consistency of supply. Every storage-tank in the fleet (some garages have as many as fifteen) is inspected twice yearly, a bottom sample being taken on one occasion, and on the other the sample is obtained from a point some 2 feet below the level of the fuel. In the event of any appreciable amounts of water or suspended matter being detected in the fuel, the tank concerned is cleaned out. To assist in this operation tanks are, where possible, installed at an angle with the horizontal, and are provided with a sludge-cock at the lowest point. It is also the practice to clean out service-tanks during the overhauling of vehicles. As a further precautionary measure, the fuel is passed through a gauze filter during its discharge from the supplier's tank-wagon, and is again filtered when being pumped from the storage-tanks to the service-pumps. It receives a third filtration while being issued from the service-pumps, filters in which are removed for cleaning at weekly intervals. Finally, a Bosch filter is fitted on each vehicle, in the fuel-line between the service-tank and the fuel-pump; this filter is of the fabric-bag type, the fabric being renewed after each 12,000 miles' service.

Maintenance Methods.

The efficient burning of the fuel is also dependent on the design of both engine and injectors. The earlier types of direct-injection engines, despite an inherent advantage in respect of both fuel consumption and maintenance costs, were very prone to give a smoky exhaust, and it was for this reason that the Board originally decided on the standardization of the air-cell or indirect-injection type of engine. Comparatively recently, however, direct-injection engines have been improved, particularly in respect of injector design, to a degree such that the smoke problem no longer exists, and it has been possible to commence operating them in numbers on the London streets.

As was indicated at an earlier stage, the fact of having obtained in some measure a satisfactory combination of engine and fuel does not in itself

ensure efficiency, this being achieved only by regular and careful maintenance. Garages are provided with Maintenance Bulletins in which the chassis (including, of course, engine and accessories) is fully described and the various measures to be employed in servicing are laid down in precise terms; these Bulletins have proved to be most valuable, particularly during a period when new equipment is being rapidly introduced. Amongst the various factors which contribute to efficient combustion, the fuel-pump and injectors must be regarded as the most important. The former controls the quantity of fuel injected per cycle, whilst the injectors determine the manner in which the fuel is sprayed into the combustion space; over-injection, unbalanced injection, or a distorted spray will lead to imperfect combustion, with possible production of exhaust smoke and adverse effect on fuel consumption. The procedure adopted in maintaining these essential parts will be described in some detail.

Fuel Pumps.

For each type of engine operated a standard fuel-pump setting is established. The setting is arrived at following bench and road tests, and on occasions employing groups of vehicles running in service. The aim is to provide adequate power, but at the same time to avoid any possibility of the production of smoke. In the case of indirect-injection engines full power is developed when the fuel-pump output is just below the point at which over-injection occurs; with the direct-injection engine the "smoke limit" is not so definite. Experience indicates that plunger outputs tend to increase with extended mileage, although to no great extent within the adjustment period laid down. It has further been found that within practical limits an increase in pump output does not adversely affect fuel consumption.

A special testing equipment, originally designed by the Board's engineers, is installed at each docking garage, and three such units are provided at the overhaul works. The apparatus, which is shown in Fig. 1, permits accurate balancing of the individual fuel-pump plungers and measurement of their output under accurately repeatable conditions, whilst the pump timing can also be set. Quite briefly, the equipment consists of six special test-type injectors, the nozzles being fitted with a cap containing a valve which converts the spray into a steady stream of liquid. The test injectors are carefully matched so that for any one apparatus the output from each is practically identical. The stream from each nozzle is directed into a channel leading to a test-fuel reserve tank, or may be caused to flow down a chute from the end of which the liquid is collected in a glass measuring-cylinder graduated in millilitres. Two racks are provided, each holding six cylinders, the racks being reversible, so that while one set is being filled, the other is drained in an inverted position. The fuel-pump under test is mounted in a cradle, and is connected to the nozzles by steel pipes of identical length and shape. The pump is driven at a standard speed of 600 r.p.m. by an electric motor, provision being made so that rotation may be clockwise or anti-clockwise, according to requirements. When any necessary adjustments have been made, the output from the plungers is measured by putting into operation a trip mechanism which causes the

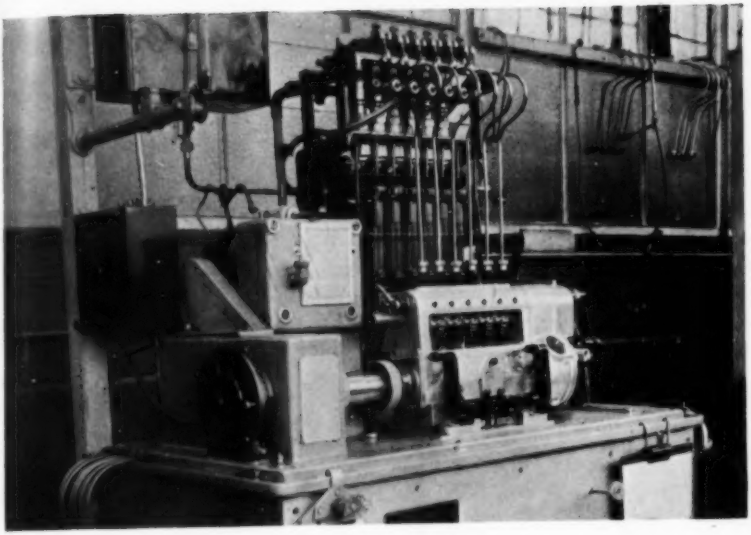

FIG. 1.
FUEL PUMP TESTING EQUIPMENT

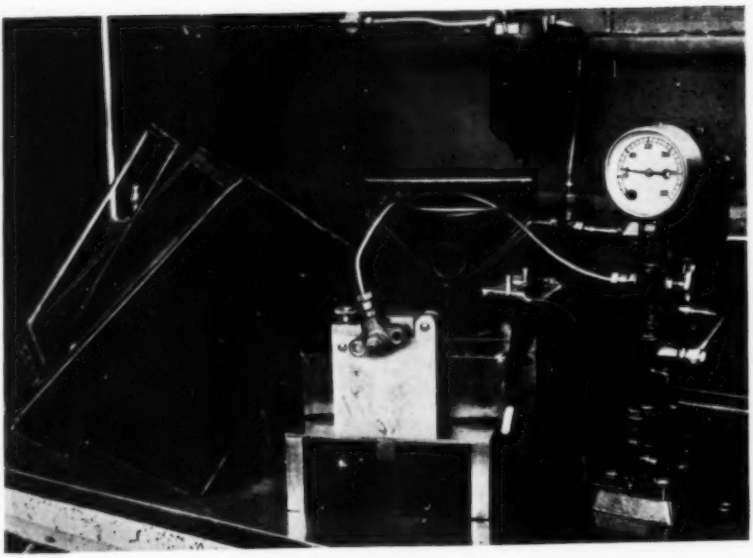

FIG. 2.
INJECTION TESTING APPARATUS.

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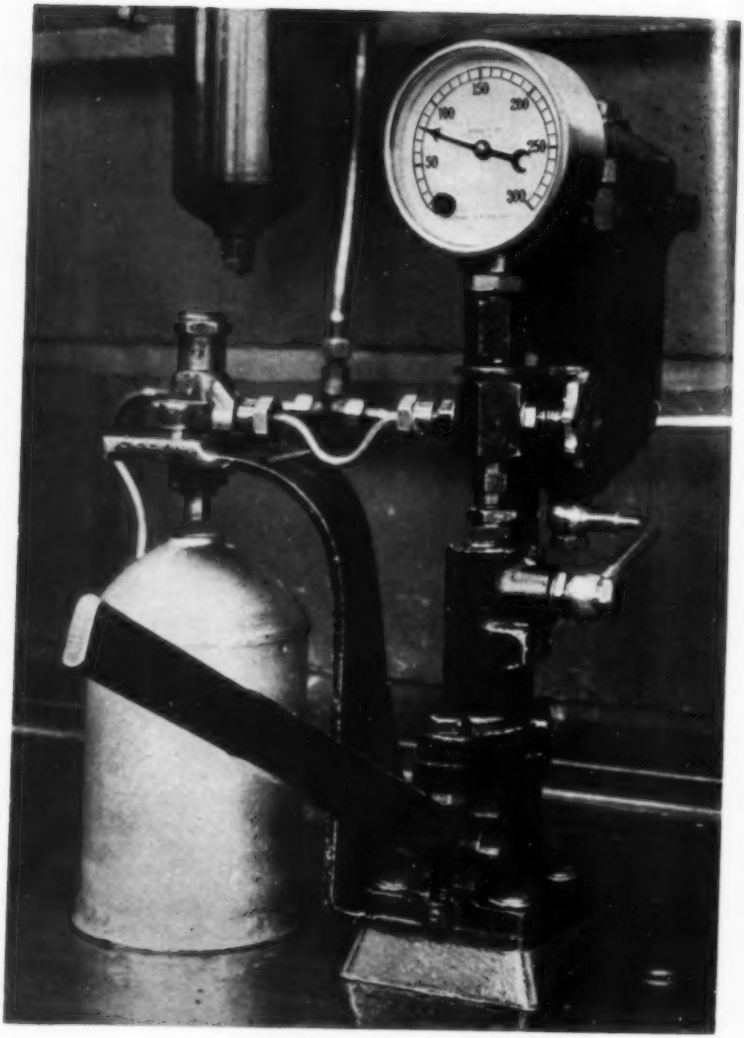

FIG. 3.
INJECTOR TESTING APPARATUS

stream from the injectors to be directed into the cylinders for a period of exactly 250 revolutions of the pump. The test speed of 600 r.p.m. has been chosen as representing the point at which variation of output with speed, amongst a number of pumps, is at a minimum; moreover, the speed corresponds to 1200 r.p.m. engine speed, an average one under conditions of operation in service. A period of 250 revolutions permits the collection of a convenient volume of liquid per cylinder (between 9 and 21 millilitres, depending on the size of the pump and type of engine concerned).

A special test fluid is used in the apparatus, it being employed also in injector-testing equipments to be described later. It is made up by mixing equal parts of white oil and kerosine of the following characteristics :—

	White Oil.	Kerosine.
Specific gravity at 60° F.	0·867	0·806
Viscosity (Redwood) at 70° F.	120 secs.	—
Closed flash-point (Pensky Marten) . . .	300° F.	125° F.

Distillation range of kerosine—approximately 160–280° C. with 50 per cent. over at approximately 210° C.

The fluid is preferable to the standard diesel fuel for testing purposes, since it is less objectionable from the point of view of the operator, and is also less prone to frothing. It is kept in a main storage-tank fitted to the apparatus, and after use flows into a reserve tank, from which it is returned to the former tank by a pump, a filter being fitted in the fuel line. To ensure absolute cleanliness during the actual test, each of the special injectors incorporates a filtering device. As a further precaution, the test fluid is discarded after a week's use.

Fuel-pumps are initially calibrated, and re-calibrated following repair, at the overhaul works. Individual plungers are balanced to within 0·2 millilitre, and the required average output is obtained by turning the throttle-stop adjusting screw. The output is checked to ensure that the plungers remain balanced, the screw being then locked and a sealed cover fitted over it. The low-speed injection stop is then adjusted so that for starting a small excess injection is provided, amounting to from 0·2 to 1·0 millilitre, according to the type of engine. The pumps are timed by an electrical device (shown on the left in Fig. 1), this method being more convenient than, although correlating with, the more usual "spill" method. Finally, the front cover-plate of the pump is refitted and the locating screw is sealed. The identification plate on the pump is stamped with a code letter indicative of the setting, and charts interpreting this code are issued to garages at six-monthly intervals, or more frequently if any standard setting has been changed in the meanwhile.

Fuel-pumps are checked at garages in respect of plunger output after each 12,000 miles in service. Any alteration required is carried out on the adjusting screw only, the seal on the cover being broken and subsequently renewed. (Re-sealing is necessary to prevent the setting being altered while the vehicle is on the road, or by night staff.) Garages are forbidden to break the seal on the front cover-plate, and any adjustment to the governor mechanism or re-balancing of plungers is invariably carried out

at the overhaul works. In respect of variation between plunger outputs, an overall tolerance of 1·0 millilitre is at present allowed before a pump must be returned for re-calibration.

One of the three fuel-pump testing equipments at the works is regarded as the standard, and is calibrated daily against a " master " test injector; the remaining equipments are checked against the standard by means of a fuel-pump used for this purpose only. A second " master " pump is employed for checking equipments at garages, this being carried out at six-monthly intervals by a specially trained inspector. On each occasion the correction for each injector is recorded on a cardboard strip fixed in a frame attached to the apparatus, so that within very close limits there is agreement between all the testing machines in use.

Injectors.

Equal care is taken in the maintenance of injectors, and after each 6000 miles in service they are dismantled, the various parts being cleaned with special tools provided for the purpose. Garages are impressed with the importance of using nothing other than these tools, and of avoiding any treatment which would tend to scratch the parts. Paraffin is used to assist in cleaning, any wiping required being done with a clean cloth, free from fluff. The use of metal polish is permitted to give a final polish to the valve, but it is forbidden to attempt to lap the valve, and if this is required, the injector complete must be returned to the works for repair. Upon re-assembly the injectors are submitted to various tests, differing somewhat according to the type.

The venturi-type injector (for indirect-injection engines) is clamped in the vertical position, and is connected to a hand-pump fitted with a pressure gauge, control valve, and supply of test fluid, and its " blowing-off " pressure is determined. The equipment is shown in Fig. 3. The pressure is set to 100 atmospheres, by adjustment of the valve-spring, if necessary. The character of the spray is carefully observed; it must be in the form of a conical, finely divided mist, free from distortion or dribble. As a subsidiary test the experienced operator notes the characteristic buzz produced when the pressure is released. The nozzle valve-seats are tested for tightness by bringing the fuel pressure to within 10 atmospheres of the operating pressure, under which conditions the nozzle face must remain dry for at least five seconds. Leakage past the valve is determined by observing the time required for the pressure to drop from 100 to 75 atmospheres, the limits being a minimum of 6 seconds and a maximum of 45 seconds. If an injector fails to meet any one of these tests, it is returned to the overhaul works for repair.

Even more care is required in the cleaning and adjustment of injectors for direct-injection engines, since the pintle orifice is of very much smaller diameter than that of the venturi-type injector, the spray produced being a narrow cone of considerable penetration. The injector cannot be set to a precise " blowing-off " pressure, but by means of shim washers fitted at the top of the spring this can be adjusted to within 10 atmospheres. While the permissible range of operating pressures is 140–170 atmospheres, all the injectors for a particular engine must be set within a 10-atmospheres range

inside these limits. The "blowing-off" pressure is again determined by connecting with a hand-pump, but since the accuracy of the spray cannot be judged by mere observation, the hand-pump forms part of a "target" testing apparatus, in which the injector is mounted horizontally (see Fig. 2). The whole of the spray must pass through a $1\frac{1}{4}$-in.-diameter hole in a plate positioned at a distance of $14\frac{1}{4}$ ins. from the injector orifice. To prevent the oil mist being breathed by the operator, the apparatus is enclosed by a hood, the top being fitted with a glass cover, hinged to facilitate cleaning. A dry-face test is also applied, the injector being required to hold a fuel pressure of 100 atmospheres for 3 seconds without appreciable leakage. Back leakage past the valve stem is determined by setting the pressure to 150 atmospheres and noting the time taken for it to fall to 100 atmospheres; the permissible limits are 12 seconds minimum and 35 seconds maximum. The test is a critical one, and to assist operators in judging the time, a simple device is provided consisting of two accurately adjusted sand-glasses mounted in a frame which can be pivoted through 180°.

Pressure-gauges fitted to injector-testing equipments are checked every six months against gauges standardized at the National Physical Laboratory. Correction figures are not given, but red lines are painted on the faces of the gauges to indicate the pressures which the various types of injectors should register when correctly adjusted; the lines are easily removable by a solvent when re-calibrating.

Exhaust Gas Analysis.

As a further measure of combustion control, recourse is made to exhaust-gas analysis, some 6000 samples in all being handled yearly. The methods employed for oil engines are similar to those adopted in respect of petrol types, and have been previously described.* In the case of samples from oil engines it is normally sufficient to determine the percentage of CO_2, since this is directly proportional to power, and, in the absence of any disturbing factors, to fuel-pump output also. To obtain comparable results it is essential for the samples to be taken under strictly standardized conditions, and for tests on the road, engine speed is maintained at 1200 r.p.m. with the accelerator pedal depressed to its fullest extent. To achieve these exacting conditions, a revolution counter is provided, whilst a load is imposed on the engine by judicious application of the brakes. It may be conceded that the analytical figures are not so clearly indicative of engine defects as is the case with samples from petrol engines. Nevertheless, the CO_2 content of the exhaust gases provides a rapid check on the correctness or otherwise of the setting of the fuel-pump on an indirect-injection engine. It is not at the moment possible to exercise so close a control with direct-injection engines, but the reasons for this are known, and a new technique is being developed. With either type of engine it is an easy matter to detect a fuel-pump the setting of which is approaching the "smoke limit," and the percentages of CO_2 in the exhaust gases corresponding to this point have been carefully established; they are in

* *Jour. Inst. Fuel*, Vol. VI, No. 27, p. 131.

the region of 13 per cent. for indirect-injection engines and 10 per cent. for direct-injection engines. This difference is, of course, largely due to the fact that the direct-injection engine utilizes a higher proportion of air than does the indirect-injection type.

Organization.

A special section is established at the overhaul works for dealing with fuel-pumps and injectors, and an individual record is maintained in respect of each of the former, being brought up to date every time the pump is received for re-adjustment. At garages the testing is deputed to one man who has received previous training in the section at the works. Results of fuel-pump tests, both prior to and following the limited adjustment permitted, are recorded on special forms, and each one of these is scrutinized by an inspector. Any irregularities revealed, such as the refitment of unbalanced pumps, or pumps exceeding the tolerance on output, are immediately followed up. The inspector is one of a small staff solely concerned with fuel-economy matters, and whose duties include periodic checking of testing equipments, exhaust-gas sampling, investigation of complaints of "fuming," and a continuous observation on fuel consumption. Data in respect of the latter are available for every vehicle in the fleet, and are collected in a weekly return which shows the average-miles-per-gallon figure for each vehicle type at all garages.

The description given in the foregoing of the various precautions taken to ensure efficient combustion of the fuel in high-speed oil engines is not exhaustive, although the items which require the most careful attention and which, if maintenance methods are relaxed, are the most likely to cause a smoky exhaust, have been dealt with in detail. Visible evidence of the success of these measures is provided by the three-thousand five-hundred oil-engined buses and coaches operated by the Board within its area.

In conclusion, the author would express his thanks to the London Passenger Transport Board for granting him permission to present this paper.

EXPERIMENTS WITH DOPED FUELS FOR HIGH-SPEED DIESEL ENGINES.*

By J. J. Broeze † and J. O. Hinze.†

Introduction.

The use of dopes may be considered to be one of the most promising methods for improving the ignition quality of diesel fuels, should such improvement appear to be necessary. In particular their use may make it possible to meet special requirements with respect to a high cetane number combined with a low cloud- and pour-point of the fuel. To take a concrete case, the authors would refer to such a combination as a minimum cetane number of 55–60 and a pour-point below −40° F. Such a combination is included in tentative and recommended specifications by the U.S.A. Navy and Army Air Corps, and a somewhat similar combination would certainly be required for many diesel aero-engines.

As ignition quality beyond 45 cetane is, in many cases, linked up with the presence in the fuel of paraffinic chains, and as the tendency to congeal at low-temperatures goes, to some extent, parallel with the amount of paraffinic chains contained in the fuel, it is clear that such special requirements can scarcely be fulfilled by any straight-run or cracked fuel. The use of low-boiling fractions seems to make an exception, which, however, has the disadvantage of greatly reducing the output of suitable fuel and the risk of involving too low a viscosity for diesel-engine practice. One has to have recourse to special treatment of fuels suitable for that purpose.

Of the other important treatments, may be mentioned hydrogenation, polymerization, mild cracking, dewaxing, admixture of pour-point depressors, acid treatment, and solvent extraction,[1] especially the latter, possibly combined with the use of dopes.

For a pour-point below −40° F. one has to start usually with a fuel of cetane number 30–35; this may be a straight-run highly aromatic and/or naphthenic fuel, or a cracked one. When from this fuel, by solvent extraction, a fuel with a cetane number of 55 is obtained, only about 50 per cent. yield would be obtained; hence this method has the same disadvantage of greatly reducing the output of suitable fuel as the use of low-boiling fractions. Moreover, by solvent extraction also the pour- and cloud-points are often raised, whereas the additional use of pour-point depressors—as *e.g.*, paraflow—would not cause a corresponding decrease of the *cloud*-point—that is, in the temperature at which filter troubles may appear.

On the other hand, a minimum of 2·5–3 per cent. by weight of even the most effective dopes would have to be added to bring the cetane number up to specification, which will call for an increase of some 20–25 cetane numbers.

Hence, to meet such a special fuel requirement the most efficient way would be to start from fuels with a low pour-point (non-waxy fuels)

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which may be extracted to give cetane numbers up to 40, and then to add 1–1·5 per cent. dope.

In other cases, where a total increase of not more than about 10 cetane numbers is required, the addition of dope only would suffice. Of course, one of the other treatments mentioned above may be used, but which of them is to be preferred, however, depends also on economical considerations.

2. Requirements from a Dope.

A dope for the improvement of the ignition quality of a fuel has to fulfil the following requirements :—

(*a*) it must be as effective as possible;
(*b*) it must be soluble in the fuel up to high concentrations;
(*c*) it should not be soluble in water;
(*d*) it should not be influenced by acidic components in fuels (unless the fuel be previously soda-treated);
(*e*) it must have a high degree of stability in storage;
(*f*) it must not be explosive under moderate temperature conditions, when in solution;
(*g*) its manufacture, yielding a constant product, should be reasonably easy;
(*h*) it should not have corrosive properties;
(*i*) it should be inexpensive.

These requirements are all more or less evident. However, it will be clear that all requirements cannot be fulfilled to the same degree without influencing each other. The requirements (*a*), (*e*), and (*f*), are more or less contradictory: the effect of a dope during the ignition period of the fuel in the engine is due entirely to its highly unstable character at higher temperatures, or, to put it in other words, to the fact that the dope molecules are easily activated, implying at the same time a greater chance of instability at lower temperature, and this the more so the more effective is the dope.

In the technical and patent literature a great number of diesel dopes are mentioned, but only a few of them fulfil the above requirements in a satisfactory way. The latter dopes belong mainly to the class of nitrates and peroxides.

Of course, the chemist has not spoken the last word on this subject, but according to the experience of the authors, the best results have, up to now, been obtained with acetone peroxide, which seems to fulfil all requirements satisfactorily, whilst good results are also obtained with ethyl nitrate, apart from some corrosion troubles.

In this paper the authors will discuss their results obtained with acetone peroxide and ethyl nitrate as dopes, and mainly with respect to :—

(*a*) their influence on the ignition delay of a fuel;
(*b*) their influence on the further stages of the combustion process;
(*c*) their influence on wear (corrosive action) and incrustations in the engine;
(*d*) various subjects, as storage tests, etc.

3. Influence of a Dope on the Ignition Delay of a Fuel.

Very little is known about the effect of a dope on the chemical processes occurring during the ignition period. The theories which may be given to explain the phenomena resulting from the effects of a dope are still in a hypothetical form. It is not the authors' intention to enter now into this physicochemical labyrinth. Only this can be put forward, that it seems possible to include the working of a dope in the theory of chain reactions.

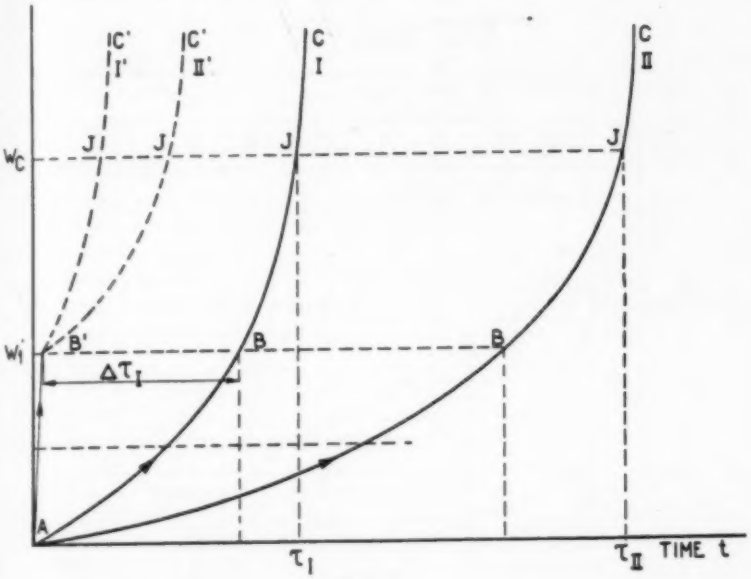

Fig. 1.

Semenoff [2] has given the following formula, based on this theory for the reaction velocity w at time t :—

$$w = A(e^{\phi t} - 1)$$

In this formula A and ϕ are dependent on the kind of molecules, pressure, and temperature. As ϕ appears in the exponent, its effect on the reaction velocity is predominant.

In Fig. 1 reaction velocity has been plotted against time, for various values of A and ϕ (curves I and II). When the reaction velocity has reached a critical value w_c, explosive reaction or inflammation occurs. The time necessary for w to reach this value (ignition delay) is the shorter the lower the oxidation stability of the molecules, and the higher the pressure and the temperature of the reacting substances.

Now we may consider the dope molecules as being of extremely low thermal stability.

In Fig. 1 the reaction of the undoped fuel is represented by curve ABC, whereas for the doped fuel it is represented by curve $AB'C'$.

The reaction velocity w_1 which results from the influence of the dope molecules, and which is proportional to the number of these molecules, will be reached practically in a time zero, so that the effect on the whole ignition delay will be found in its reduction with the value $\Delta\tau$.

From the exponential shape of the curves I and II it may be deduced first that this reduction in delay time is the greater the higher the value of τ, and secondly, that reduction of delay time per unit of dope percentage in the

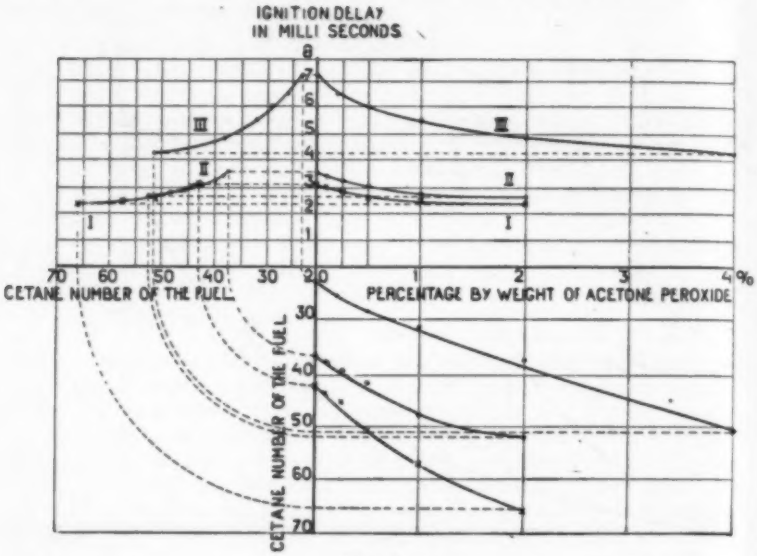

FIG. 2.

ENGINE: SLOW SPEED, HORIZONTAL ENGINE WITH DIRECT INJECTION.
FUELS: (I) STRAIGHT RUN MIXED BASE.
(II) STRAIGHT RUN ASPHALTIC BASE.
(III) STRAIGHT RUN AROMATIC BASE.

fuel is lower the higher is the percentage of dope. Hence one may expect that the effect of a dope, expressed in terms of the reduction of the ignition delay, will be dependent on the ignition delay of the undoped fuel, which means the ignition quality of the fuel and/or the engine conditions and the amount of dope already added to the fuel.

Experimental results of the effect of a dope on the ignition delay will be discussed with respect to the dependence on :—

(*a*) the chemical activity of the undoped fuel;
(*b*) the physical delay of the fuel;
(*c*) the engine conditions.

These experimental results seem to correlate fairly well with the above-given representation of the working of a dope.

(a) *Chemical Activity of the Undoped Fuel.* Fig. 2 gives the ignition delays in milliseconds and the cetane numbers for three fuels of different base and for various percentages of acetone peroxide added to these fuels. All three fuels are straight-run gas oils; fuel I is of mixed base, fuel II of asphaltic base, and fuel III is a highly aromatic one. The delay measurements were carried out on a low-speed single-cylinder horizontal diesel engine (bore and stroke : 210 × 370 mm.), four-cycle, direct-injection, at a speed of 275 r.p.m. and a b.m.e.p. of 1·55 kg./cm.^{2} In Fig. 2 the following may be noted :—

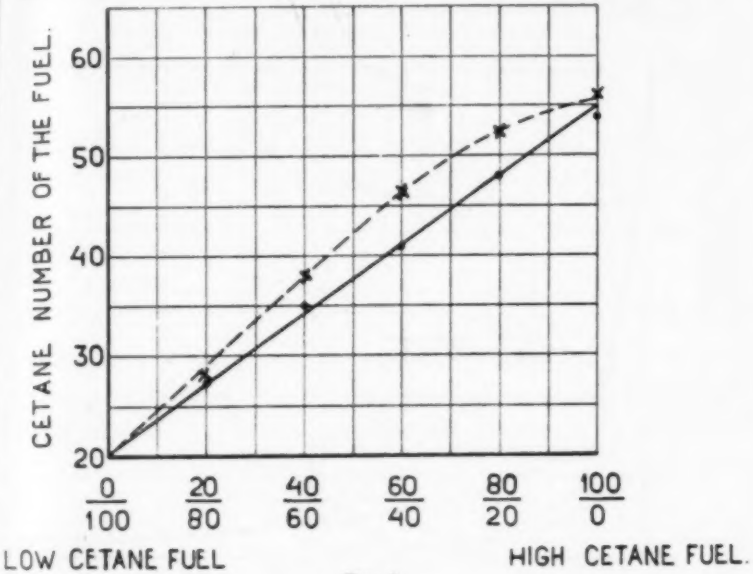

FIG. 3.

●———● BLENDS OF A LOW CETANE FUEL AND AN UNDOPED HIGH CETANE FUEL.
×– – – – – × BLENDS OF A LOW CETANE FUEL AND A DOPED FUEL OF HIGH CETANE NUMBER.

First the effect of the dope, expressed in the decrease of the ignition delay, is greater in a low-cetane fuel than in a high-cetane fuel. However, due to the hyperbolic character of the curve of cetane number *versus* ignition delay, the effect of a dope when expressed as the increase in the cetane number is greater in a high-cetane fuel than in a low-cetane fuel.

Secondly, comparing two fuels of equal cetane number, one undoped and the other doped, and further adding equal amounts of dopes to both fuels, then the effect of this dope addition is greater on the undoped than on the doped fuel. The consequence of this will be that when a doped fuel of high cetane number is blended with an undoped low-cetane fuel, a linear relation between the cetane numbers of the blends and the weight percentage of the blending agents no longer exists, as would occur if both blending agents were undoped fuels (Fig. 3).

Thirdly, the effect of a dope, expressed either as an increase in the cetane number, or as a decrease of the ignition delay, decreases the more dope has already been added to the fuel.

These results are more clearly demonstrated when one determines the decrease of ignition delay per unit of percentage of dope—that is, the differential quotient $\frac{\partial \tau}{\partial p}$, where p denotes the percentage of dope. In

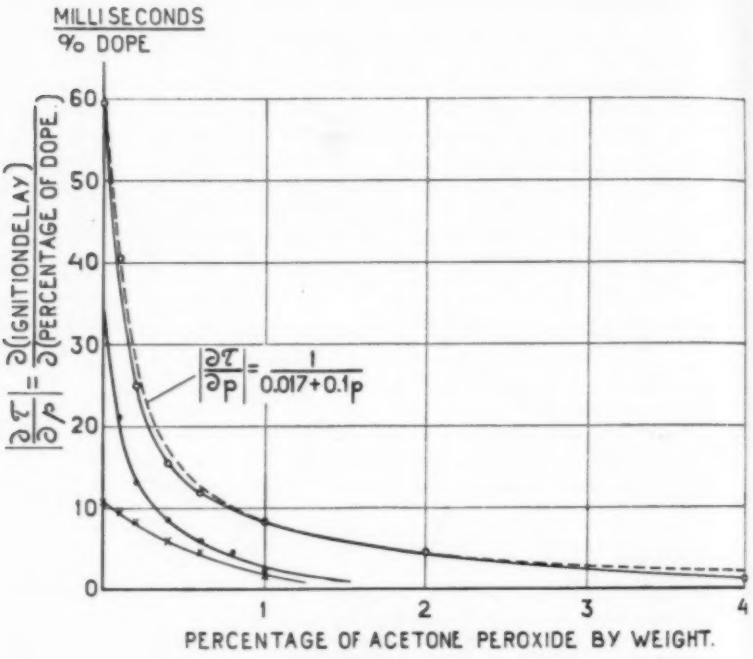

FIG. 4.

ENGINE: SLOW SPEED HORIZONTAL ENGINE WITH DIRECT INJECTION.
FUELS: (I) STRAIGHT RUN MIXED BASE.
(II) STRAIGHT RUN ASPHALTIC BASE.
(III) STRAIGHT RUN AROMATIC BASE.

Fig. 4 the value of $\frac{\partial \tau}{\partial p}$ for the three fuels has been plotted against the percentage of dope p.

(b) *Physical Delay of the Fuel.* As the working of a dope is purely chemical, it is clear that its effect will be greater the greater is the "chemical" part of the ignition delay, for it could do nothing to shorten the "physical delay," which is due to the absence of sufficient vapours in the very first moment of the ignition delay.[3, 4] With light distillate fuels many experiments have shown that this physical delay is usually

very small with respect to the total delay. In heavy fuels the physical delay will become relatively more important, hence the effect of a dope will then become relatively less great. This is clearly shown in Fig. 5, where a comparison is made between a straight-run gas oil of asphaltic base (curves I) and a peanut oil, Arachis oil (curves II), both of practically

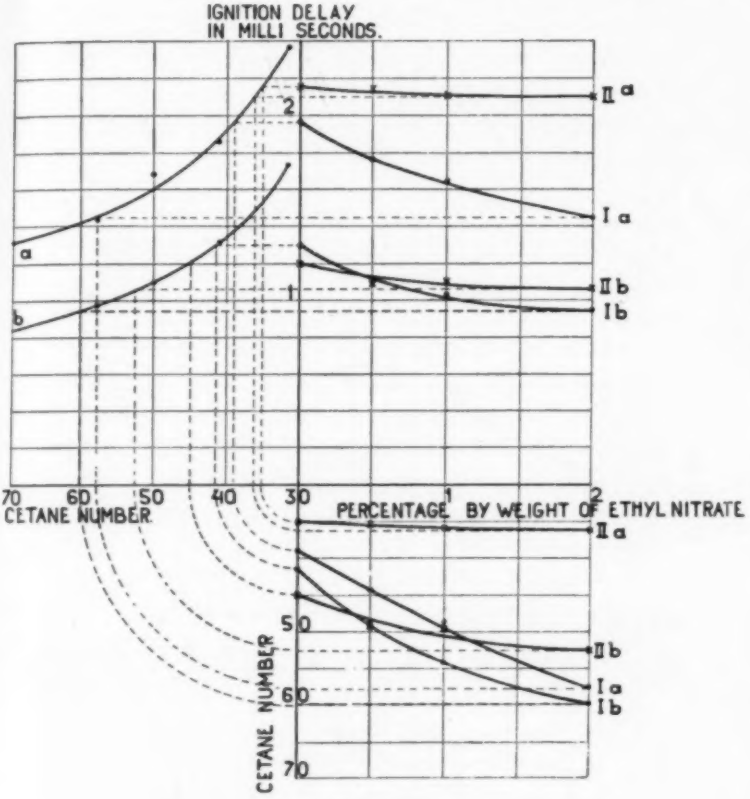

FIG. 5.

ENGINE: HIGH SPEED, SEPARATE SWIRL-CHAMBER.
FUELS: (I) STRAIGHT RUN ASPHALTIC BASE.
(II) PEANUT OIL (ARACHIS).
a = LOW INJECTION PRESSURE.
b = HIGH INJECTION PRESSURE.

the same ignition quality. Ethyl nitrate was used as a dope. The tests were carried out on a single-cylinder, high-speed, four-stroke vertical diesel engine, fitted with a separate swirl-chamber (bore and stroke 120 × 140 mm.), at a speed of 1300 r.p.m. and a b.m.e.p. of 2·5 kg./cm.^{2} In Fig. 5 the curves "*a*" refer to tests at which the opening pressure of the injection

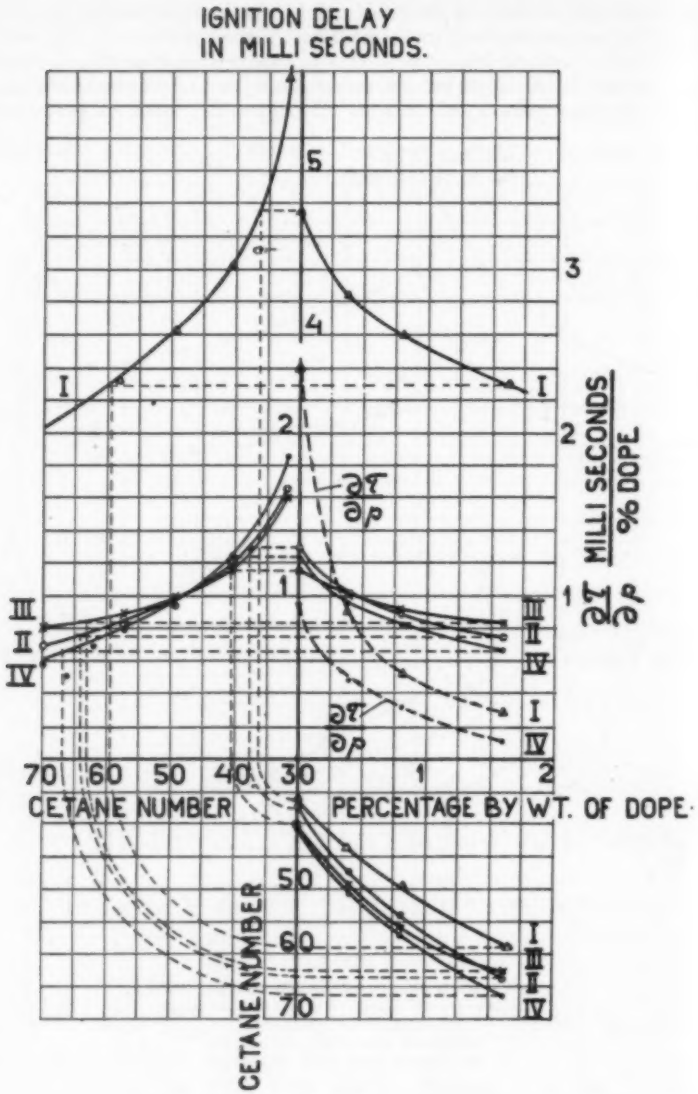

FIG. 6A.

ENGINES: (I) SLOW-SPEED DIRECT INJECTION.
(II) HIGH-SPEED DIRECT INJECTION.
(III) HIGH-SPEED SEPARATE SWIRL-CHAMBER.
(IV) HIGH-SPEED SEPARATE SWIRL-CHAMBER.

FUELS: STRAIGHT-RUN, ASPHALTIC BASE, WITH ACETONE PEROXIDE AS A DOPE.

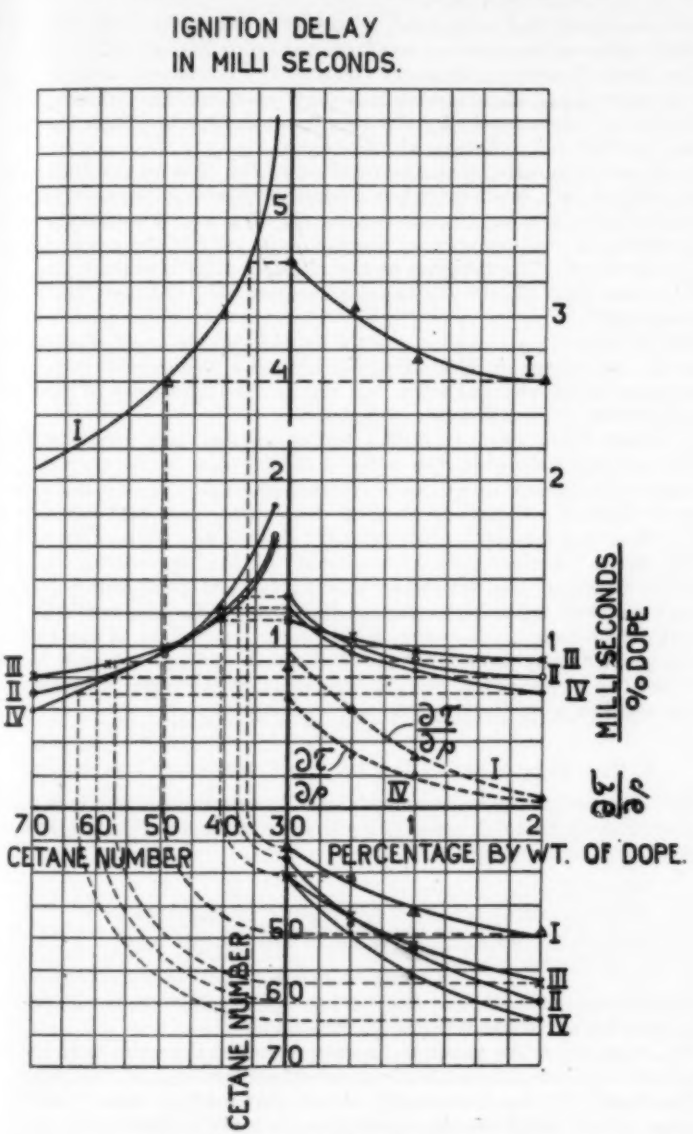

FIG. 6B.

ENGINES: (I) SLOW-SPEED, DIRECT INJECTION.
(II) HIGH-SPEED, DIRECT INJECTION.
(III) HIGH-SPEED, SEPARATE SWIRL-CHAMBER.
(IV) HIGH-SPEED, SEPARATE SWIRL-CHAMBER.

FUELS: STRAIGHT-RUN, ASPHALTIC BASE, WITH ETHYL NITRATE AS A DOPE.

nozzle was fixed at 150 kg./cm.^{2}, whereas the curves "*b*" refer to tests at which this opening pressure was increased up to 300 kg./cm.^{2}

The chemical nature of the peanut oil is such that a short chemical delay can be expected. The effect of this short chemical delay, however, is spoiled to a certain extent by the very low volatility and high viscosity of the oil—that is, by the long physical delay.

At the lower injection pressure the effect of the dope on the peanut oil (curve II*a*) is very small indeed, whereas this effect on the gas oil has a normal value (curves I*a*, compare also Fig. 6). When the injection pressure is increased, finer atomization of the fuel, especially of the more viscous one, is obtained. The influence on the physical delay is evident, and the effect of the dope will now be increased (curves II*b*), although this effect remains small.

For the sake of completeness, it must be said that the small effect of the dope in the peanut oil is attributable not only to the relatively great importance of the physical delay, but also to the high degree of chemical activity of the original fuel (see (a) p. 661).

(c) *Engine Conditions.* In high-speed engines, especially in engines with a hot turbulence-chamber, the value ϕ in the formula for the reaction velocity will be greater than in low-speed engines. This, however, also means a lower effect of a dope, expressed in delay time, in a high-speed (hot) engine than in a low-speed (cold) engine. Figs. 6*a* and 6*b* show the results of the effect of acetone peroxide and ethyl nitrate, respectively, in four different engines. The differences between the low-speed engine (curves I) and the three other high-speed engines (curves II, III, and IV) are clearly demonstrated. However, due to the steeper shape of the cetane-*versus*-ignition-delay curves for the high-speed engines, not only is the undoped fuel higher rated, but also the effect of the dope, expressed in cetane number, is relatively greater in these engines.

4. The Effect of a Dope on the Combustion Process.

Fig. 7 represents the well-known "ideal" pressure diagram (I) in comparison with the actual diagram (II) with the four stages of the combustion process, as introduced by Ricardo:—

Stage 1, ignition delay;
Stage 2, combustion of the fuel injected during stage 1;
Stage 3, ignition and combustion of fuel injected later;
Stage 4, after burning.

The influence of a dope on stage 1 has already been dealt with above. The three further stages will now be considered.

These stages of the pressure diagram represent the main part of the combustion process as far as development of heat is concerned. In previous publications [4, 5] it has been amply shown that for light diesel fuels this process, given certain engine conditions, is mainly determined by the ignition quality and the volatility (and/or viscosity) of the fuel. Combustion, once initiated, is then governed practically by the state reached by the mixing of air and injected fuel (stage 2 of Fig. 7) and by the way in which mixing of subsequent injected fuel with the remaining air takes

place (stage 3 of Fig. 7). Therefore it has not yet been possible to detect clearly an influence of the chemical composition of the fuel on the combustion process, apart from the influence determined by the ignition quality. Of course, the chemical composition of the fuel plays its part, as it effects, through the C : H ratio, the amount of heat liberated during combustion.

Referring to Fig. 1, which may also be representative of the process occurring in a nucleus, in which combustion originates, it may be observed that beyond the point of inflammation an influence of the chemical composition of the fuel on the reaction velocity would scarcely be noticeable.

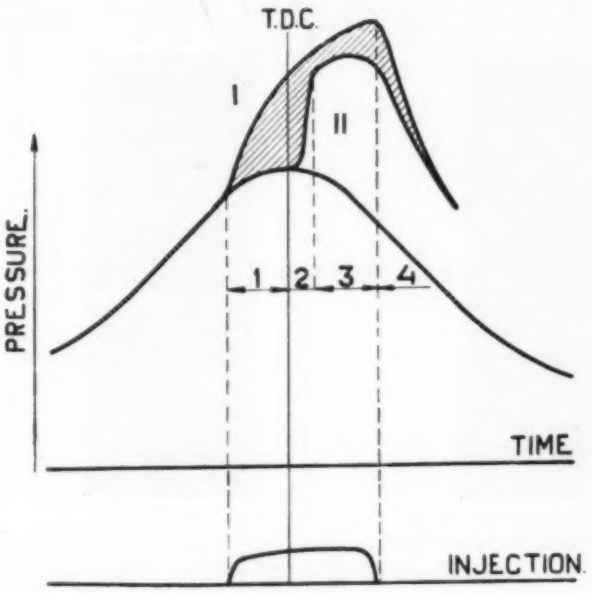

FIG. 7.

In the light of these facts, an effect of dope addition to a fuel on the combustion process as a whole may be expected only in the shape of an effect on ignition quality, the more so when the small percentages are considered in which dopes are added to a fuel.

This has been confirmed by experiments in the diesel engine. In engine practice, the combustion process can be investigated directly by studying the pressure diagram, and indirectly by comparing the output, specific fuel consumption, and exhaust temperature.

Fig. 8 shows a series of pressure diagrams on two high-speed diesel engines, one being of the direct-injection type, the other of the separate swirl-chamber type. An undoped straight-run paraffinous gas oil with a cetane number 58 and a straight-run, mixed base gas oil doped with acetone peroxide in different percentages are compared. Differences in the diagrams for the undoped and doped fuels of practically equal cetane

number can scarcely be found, even if a close investigation is made of the different stages of combustion, by analysing the diagram as to the rate of heat liberation, by means of well-known methods, based on simple thermodynamical laws for ideal gases.

In Fig. 9 this rate of heat liberation, expressed in calories/degree crank-angle, is given for the undoped and doped fuel of equal cetane number, calculated from the pressure diagrams obtained on the direct injection engine (Fig. 8, numbers 8 and 10).

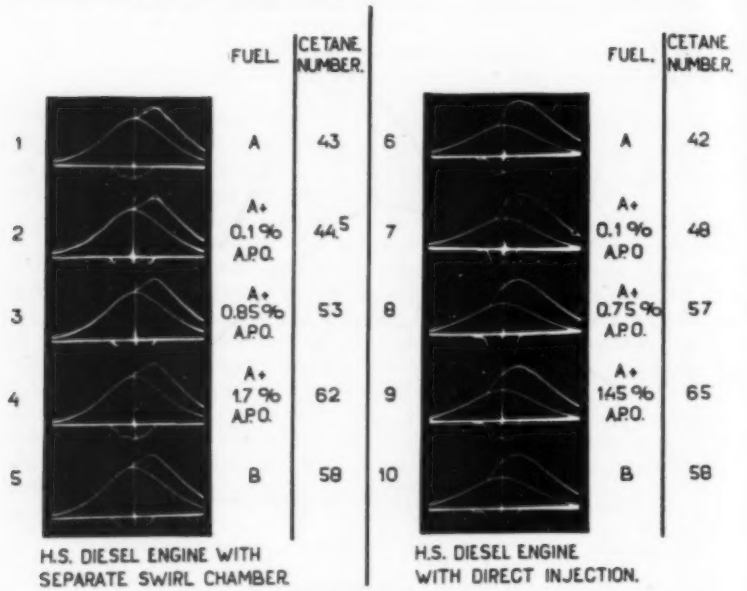

FIG. 8.

A slight difference is found, which, apart from errors of measurement, may be attributed to differences in specific gravity and calorific value.

In Fig. 10 are given the specific fuel consumption, exhaust temperatures, maximum pressure, and maximum rate of pressure rise for a fuel doped with various percentages of acetone peroxide. These results have been obtained on a 12-cylinder, V-type, rail-car engine, with direct injection, the output being maintained at 300 b.h.p. at 1400 r.p.m. (b.m.e.p. = 5·3 kg./cm.^{2}). The above-mentioned quantities are plotted against the percentage of dope added to the fuel and against the corresponding cetane numbers (the latter figures have been determined on another direct-injection engine). As Fig. 10 shows, fuel consumption and exhaust temperatures increase with increasing dope percentage or cetane number, which is in accordance with what is generally observed in direct-injection engines.[5, 7] The lower

graph also shows the results obtained with an undoped fuel of 58 cetane number and of practically the same viscosity and distillation range (points *A*). Specific fuel consumption is now somewhat smaller than for the

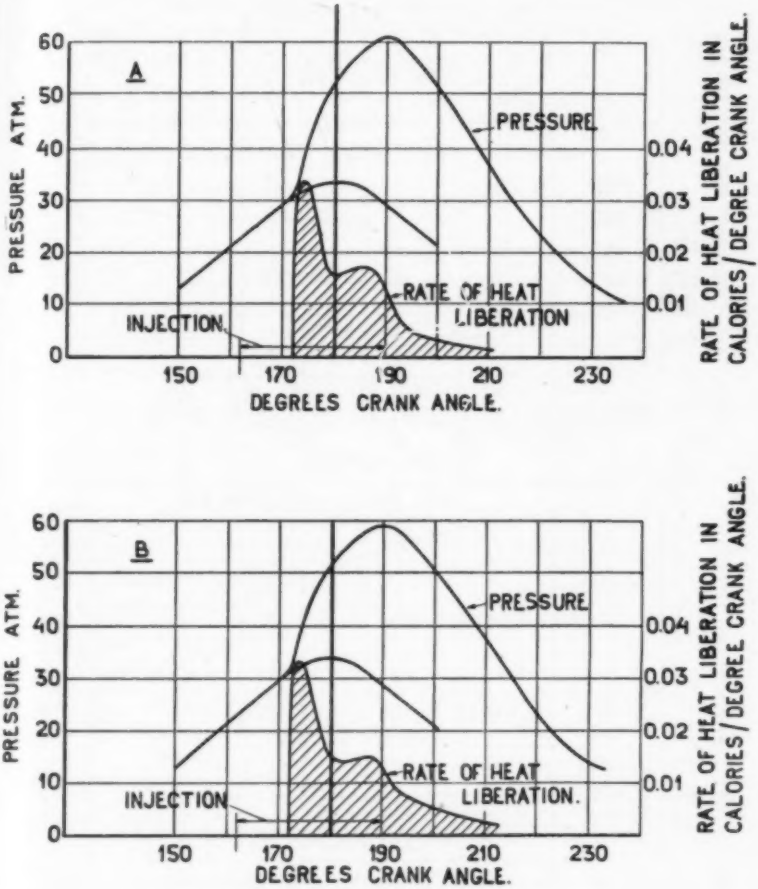

FIG. 9.

ENGINE: HIGH-SPEED DIRECT INJECTION.
FUELS: A. S.B. MIXED BASE WITH ACETONE PEROXIDE.
B. S.B. PARAFFINOUS BASE.

corresponding doped fuel, but this may be ascribed to the difference in calorific value between both fuels, which in this case amounts to about 2 per cent. in favour of the undoped fuel. The maximum pressure on the undoped fuel is somewhat lower. This may be explained by a difference in specific gravity, so that with the same pump and fuel-valve character-

istics, more fuel is injected per unit of time for the heavier fuel and, when burning, more heat is liberated per unit of time, even when the difference in calorific value is taken into account. On the other hand, the spreading

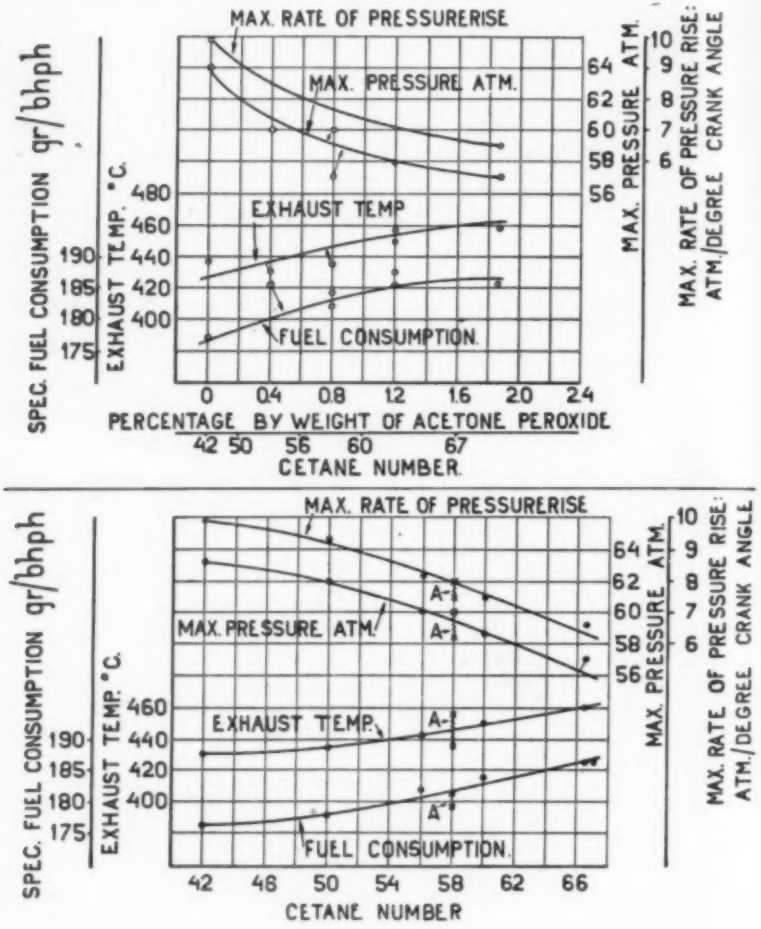
MAX. RATE OF PRESSURERISE
MAX. PRESSURE ATM.
EXHAUST TEMP
FUEL CONSUMPTION
SPEC. FUEL CONSUMPTION gr/bhph
EXHAUST TEMP. °C.
MAX. PRESSURE ATM.
MAX. RATE OF PRESSURE RISE: ATM./DEGREE CRANK ANGLE
PERCENTAGE BY WEIGHT OF ACETONE PEROXIDE
CETANE NUMBER
42 50 56 60 67
0 0.4 0.8 1.2 1.6 2.0 2.4
42 48 50 54 58 62 66

FIG. 10.

in the test data for the maximum pressures should warn against overestimating the importance of this deviation.

A more complete comparison between undoped fuels and fuels doped with ethyl nitrate, with respect to fuel consumption and exhaust temperatures, is given in the following Fig. 11, where these values have been plotted against the ignition delay of the fuels. The fuel-consumption figures have been

corrected for differences in calorific value of the various fuels. The results, which have been obtained on a single-cylinder, high-speed diesel engine of the direct-injection type at 1500 r.p.m., b.m.e.p. 7·4 kg./cm.^{2} are self-evident.

5. Influence of a Dope in a Fuel on Wear and Incrustations in the Engine.

Numerous experiments on wear and incrustation problems have so extended our knowledge on the subject as to allow the authors to predict what results will be obtained in this respect with a certain fuel.

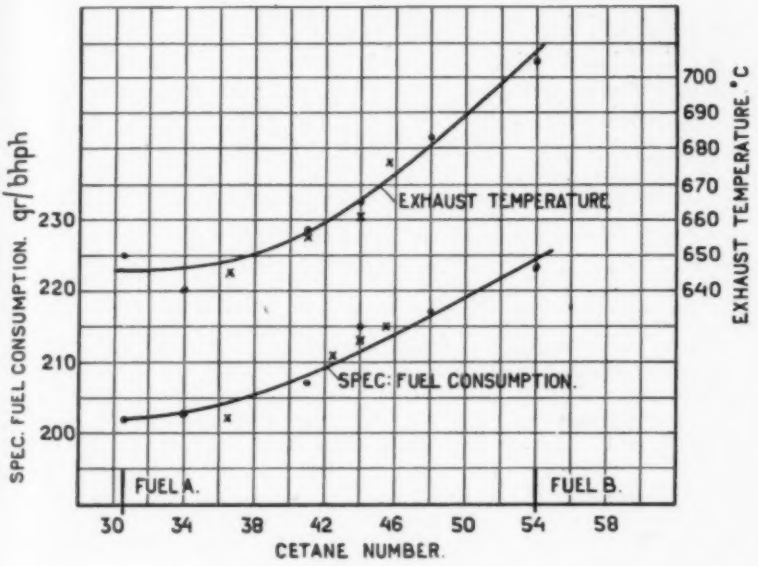

Fig. 11.

ENGINE: HIGH-SPEED DIRECT INJECTION.
FUELS: • BLENDS OF A LOW CETANE FUEL *A* AND A HIGH CETANE FUEL *B*.
× LOW CETANE FUEL *A* WITH DOPE ADDITION.

Wear is mainly affected by: suspended matter (sand, dirt) and water (in quantities exceeding 2 per cent.), ash content (certain metallic oxides), high sulphur content, and by bad or incomplete combustion.[8]

The origin of incrustations may be sought in incomplete combustion, due to poor ignition quality, high residue content, and/or high viscosity (poor atomization and poor evaporization) of the fuel.[5-9]

Apart from the effect on the ignition quality, none of the other fuel properties will be unfavourably affected by a good ignition dope. Hence one can scarcely expect any other effect of a dope on wear and incrustation than will be determined by the increase of the ignition quality.

Table I gives an example of a complete analysis of an undoped fuel *A*, of a base fuel *B*, and of the latter fuel doped with about 1 per cent. acetone peroxide, the fuel *A* and the doped fuel *B* both having equal ignition quality.

TABLE I.

Fuel.	A.	B.	B + 1% Acetone Peroxide.
Specific gravity, 15/4° C.	0·843	0·865	0·867
Viscosity, c.c., 50° C.	3·09	2·72	2·82
Acidity	<0·05	0·7	0·70
Pour-point, ° C.	−7	<−20	<−20
Cloud-point ° C. (after refining with 20% Terrana)	+1	−21	−20
Sulphur content, % by wt.	0·7	0·9	0·9
Ash content, „ „	traces	nil	nil
Asphaltenes, „ „	nil	nil	nil
Conradson carbon test	zero	0·02	0·02
Conradson carbon test in 10% bottoms	0·04	0·09	0·09
Water content	nil	traces	traces
Bromine value	<1	<1	<1
Upper calorific value, cals.	10,897	—	10,756
Distillation I.B.P., ° C.	237	227	227
10% by vol., ° C.	263	246	246
65% „ „ „	298	288	288
90% „ „ „	332	322	322
F.B.P.	370	345	345

Some long duration tests lasting over a total of 80 hrs., under various loads and speeds, have been carried out on two single-cylinder, high-speed engines, both with the fuels *A* and *B* + dope, mentioned in Table I.

One engine is a direct-injection engine (bore and stroke 108 × 152 mm., developing 15 b.h.p. at 1500 r.p.m.), the other is fitted with a separate swirl-chamber (bore and stroke 117 × 149 mm., developing 15 b.h.p. at 1500 r.p.m.).

Table II gives the weight of incrustations on various parts of the combustion space. (The tests on the first mentioned engine have been duplicated.)

TABLE II.

Weight of Incrustations in Grams on Various Parts of the Engine after Long Duration Tests of 80 Hours.

Engine Fuel.	Direct-Injection Engine.				Engine with Separate Chamber.	
	A.		*B* + dope.		*A*.	*B* + dope.
Cylinder head	1·96	2·08	2·4	2·9	2·47	2·70 gms.
Piston crown	0·96	1·04	1·08	1·18	0·78	0·96 „
Piston ring grooves	0·12	0·20	0·20	0·38	0·57	0·94 „
Nozzle	0·68	0·12	0·12	0·14	—	—
Separate chamber + nozzle	—	—	—	—	0·94	0·80 „

In both engines the amount of incrustations is slightly higher with the doped fuel, which may be ascribed to the difference in residue content (compare the figures for the Conradson Carbon test in 10 per cent. bottoms).

Taking into account, moreover, that these differences are of the same order as the spreading in test results, the conclusion may be reached that the dope did not affect these results except in so far as it affected the ignition quality of the fuel.

Neither did the results on wear of piston-ring and cylinder liner give marked differences between both fuels. For the doped fuel, the piston-ring wear is somewhat higher (Table III), but the liner wear is less (Table IV, where the increase in cylinder diameter after each test is given, measured at the spot opposite the upper ring in top dead centre position of the piston).

TABLE III.

Decrease of the Piston-Ring Weight in m *Grams after each Test.*

Engine.	Direct-Injection Engine.				Engine with Separate Chamber.	
Fuel:	*A.*		*B* + dope.		*A.*	*B* + dope.
Piston ring 1	158	161	193	228	398	505 m. gm.
„ „ 2	51	42	54	58	94	107 „
„ „ 3	39	32	44	51	70	49 „
„ „ 4	24	18	26	30	61	39 „

TABLE IV.

Increase in Cylinder Diameter after each Test.

Engine.	Direct-Injection Engine.				Engine with Separate Chamber.	
Fuel:	*A.*		*B* + dope.		*A.*	*B* + dope.
Perpendicular to crankshaft .	0·018	0·015	0·004	0·010	0·010	0·004 mm.
Parallel to crankshaft . .	0·009	0·009	0·001	0·007	0·007	0·002 „

For sake of completeness, a sample of each fuel was circulated, for 300 hrs., through a Bosch-injection pump and injectors, but no traces of corrosion or deposits on the pump- and injector-elements could be found after these tests.

6. VARIOUS RESULTS.

Besides the above results on the behaviour of doped fuels in the diesel engine, there are still some other points which may be of importance—*e.g.*, their stability during storage and the question of safety (explosiveness).

Storage for several years of pure ethyl nitrate did not have a measurable influence on its effectiveness as a dope.

The experience of the authors have so far only covered storage tests with acetone peroxide of a period of over 10 months. These tests have been made in connection with fuels of various bases; during storage in small drums, the doped fuels were kept at a constant temperature of 30° C. (tropical conditions) and in contact with iron, zinc, and water. Table V summarises the results giving cetane numbers of the undoped base fuels and the doped fuels before and after storage. These tests have proved the practical stability, during storage, of a fuel doped with acetone peroxide.

From both dopes investigated, the acetone peroxide, which, in the pure state, is obtained in form of white crystals, has an explosive character. When in solution, however, this explosive character is reduced practically to zero. At room temperature acetone peroxide is soluble in gas oil up to a maximum concentration of 5–6 per cent.

TABLE V.

Fuel.	Percentage of Dope by Weight.	Cetane Numbers of—			
		Base Fuel.	Fuel + Dope (Acetone Peroxide). Storage—		Duration of Storage.
			Before.	After.	
S.R. asphalt-base gas oil .	1·03	42	51	50	4 months
Clear cracked gas oil. .	1·56	36	50	51·5	10 „
S.R. mixed base gas oil I.	1·00	38·5	46·5	46·5	10 „
„ „ „ „ „ II.	1·00	34	44·5	41	10 „
„ „ „ „ „ III.	1·00	38·5	45·5	43	10 „

The authors will conclude the paper by giving some data on the effect of acetone peroxide or ethyl nitrate on the flash-point of the fuel, which, of course, is of practical importance. The flash-points have been determined according to the Pensky-Martins closed-cup method. The results, given in Table VI, show that acetone peroxide as a dope has no important effect on the flash-point when any trace of acetone is removed by washing the doped fuel with water.

Ethyl nitrate causes an appreciable decrease of the flash-point, which in the case mentioned has brought the flash-point under the value tolerated in many specifications (compare A.S.T.M. specifications).

TABLE VI.

	Fuel.	Flash-point, ° C.
I	S.R. asphalt-base gas oil	70
II	I + 2% acetone peroxide	61
III	I + 7% acetone peroxide	51
IV	III, but washed with water	68
V	S.R. mixed-base gas oil	72
VI	V + 2% acetone peroxide	67
VII	VI, but washed with water	71
VIII	S.R. mixed-base gas oil	89
IX	VIII + 2% ethyl nitrate	59

APPENDIX.

Some interesting properties of the effect of a dope on the ignition delay may be deduced theoretically from the formula, given by Semenoff :—

$$w = A(e^{\phi t} - 1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

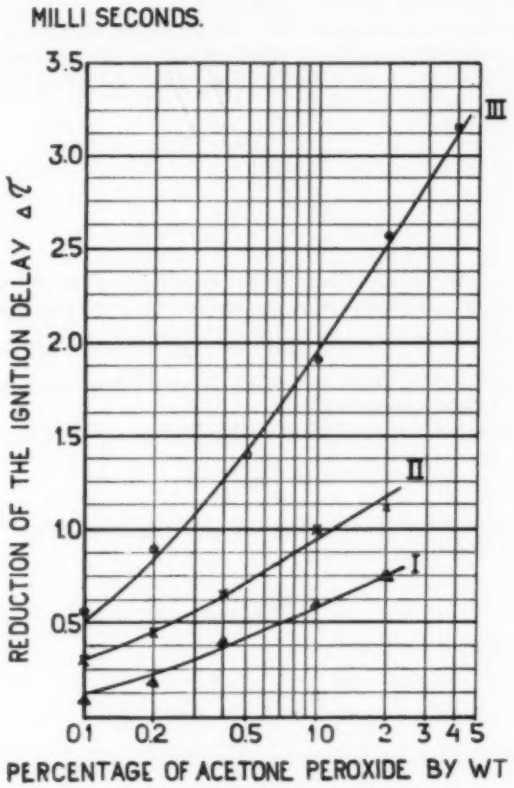

FIG. 12.

ENGINE : SLOW SPEED, DIRECT INJECTION.
FUELS : (I) S.R. MIXED BASE Δ———Δ.
(II) S.R. ASPHALTIC BASE x———x.
(III) S.R. AROMATIC BASE o———o.
THE FULL DRAWN CURVES REFER TO THE THEORETICAL FORMULA :

$$\Delta\tau = \frac{1}{\phi} \ln\left(1 + \frac{\phi t}{A} p\right)$$

For reactions which lead to inflammation, and excluding the initial periods for small values of t, unity may be neglected with respect to $e^{\phi t}$, and formula (1) may be written :—

$$w = Ae^{\phi t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Integration of this formula gives :—

$$c = \int_0^t w dt = \frac{A}{\phi}(e^{\phi t} - 1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where c is the amount of reactive substances, which may be considered as peroxides in their most general signification.

Assuming that when a dope is added to a fuel, the reaction starts with an amount of peroxides, practically proportional to the percentage of dope, then the effect of the dope on the ignition delay is a reduction of this delay with $\Delta\tau$, given by the formula :—

$$\epsilon p = \frac{A}{\phi}(e^{\phi\Delta\tau} - 1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

or :

$$\Delta\tau = \frac{1}{\phi}\ln\left(1 + \frac{\phi\epsilon}{A}p\right)^{*} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where ϵ = a constant dependent on the effectivity of the dope.

Plotting on a logarithmic scale $\Delta\tau$ against the percentage p of dope in the fuel, a curve will be found which for high values of $\frac{\phi\epsilon}{A}p$ is practically linear. Fig. 12 gives these curves for three different fuels with acetone peroxide as a dope (compare Fig. 2).

For the undoped fuel the ignition delay is given by the formula :—

$$\tau = \frac{1}{\phi}\ln\frac{w_c}{A} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

With formula 5 for the reduction $\Delta\tau$ of the ignition delay, the ignition delay of the doped fuel will be :—

$$\tau_1 = \frac{1}{\phi}\ln\frac{w_c}{A + \epsilon\phi p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

from which may be deduced :

$$\frac{\partial\tau}{\partial p} = \frac{-1}{\epsilon\phi^2(A + \epsilon\phi p)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

giving a hyperbolic relation between $\frac{\partial\tau}{\partial p}$ and p.

As Fig 4 shows, the experimental results correlate fairly well with this relation.

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* This formula has been deduced by L. J. Oosterhoff and P. L. Kooyman (Amsterdam Laboratory of the Royal Dutch Shell). The authors wish to express their sincere gratitude for their suggestions in respect to this subject. Also the authors are much indebted to their collaborator Dr. G. H. Reman for his co-operation.

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THE APPLICATION OF GRAPHICAL AND STATISTICAL METHODS OF HYDROCARBON ANALYSIS TO DIESEL FUELS.*

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SYNOPSIS.

It does not appear to be desirable at the present time to derive a new formula for the correlation between chemical composition and the ignition delay of diesel fuels, but this might be possible in the near future if more data on accurately analysed diesel fuels with known cetene values were available.

If the influences of various percentages of different dopes are not taken into consideration, and attention is restricted, therefore, to the examination of hydrocarbon mixtures, then the work started by Kreulen is promising. This is confirmed by the authors' own results.

A more thorough investigation of a large number of diesel fuels will be necessary in order to study the influence of chemical composition on the cetene or cetane value. In this respect it will be advisable to examine a large number of hydrogenated fuels, practically free from sulphur-, nitrogen-, or oxygen-containing bodies, together with extracts and raffinates derived from these fuels, and also oils obtained by polymerizing olefines or olefine mixtures.

THE ring-analysis method developed by the authors enables the number of rings in saturated hydrocarbon mixtures to be determined with a high degree of accuracy. The advantage of this method is that it demands only a certain number of physical constants—*e.g.*, specific gravity, refractive index, mean molecular weight, aniline point, etc. Many of these constants can be determined easily, although some of them (*e.g.*, mean molecular weight) demand some experience. It seems that the ring-analysis method, which can also be called the specific refraction-molecular weight method, has now been adopted in the majority of those countries which are interested in the analysis of hydrocarbon mixtures. Two years ago it was shown, by the ultimate analysis of several saturated hydrocarbon mixtures, that the method has a high degree of accuracy.

Since the method is based on values for the atomic refractions of carbon and hydrogen, it can easily be understood that the greater the progress made in the preparation of pure hydrocarbons, the more accurately can these values be calculated and the higher becomes the accuracy of the method.

Although the method was at first employed for the analysis of saturated hydrocarbon *mixtures* of higher molecular weight, it has also proved of value for testing preparations of pure individual saturated hydrocarbons. The method has been verified by the ultimate analysis of mixtures having a *molecular weight above* 250.

In the analysis of unsaturated mixtures the aromatic ring content has also been taken into consideration, so that it is possible to represent the composition of an unsaturated olefine-free hydrocarbon mixture by :

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* Paper presented for discussion at the Morning Session (A), 24 May, at the Summer Meeting of the Institute of Petroleum held in Birmingham, 22–24th May, 1939.

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Per cent. aromatic rings *
Per cent. naphthenic rings
Per cent. paraffinic side chains.

It must be emphasized that such an expression for the analysis of, *e.g.* a lubricating-oil fraction is based on certain suppositions concerning the type of rings (rings with six or with five carbon atoms, etc.) present. It is also more convenient to express results in percentage of the carbon atoms present as aromatic rings, as naphthenic rings, and as paraffinic side-chains.† Such a suggestion has already been made by Kreulen.

As mentioned above, the greater the progress made in the preparation of pure hydrocarbons and in the knowledge of the types of hydrocarbons present in hydrocarbon mixtures, either natural or synthetic, the more accurate will become the methods of analysis. This is particularly the case with an extension of the graphical statistical method worked out in recent years by Dr. J. J. Leendertse in which the specific parachor was introduced. This method enables one to estimate the degree of branching.

As already stated the method is suitable for mixtures with molecular weight above 250. Diesel fuels have a mean molecular weight of about 200 to 260 and it is evident that we come close to the limit of application, and such definite conclusions as were reached in the investigations of lubricating oil fractions cannot be attained.

The graphical statistical methods will not be strictly necessary for the analysis of *gasoline fractions*.‡ For mixtures boiling below 150° to 200° C. the constituents can be isolated. Analytical rectification enables individual hydrocarbons to be separated. The method last mentioned has also been successfully applied to the isolation of the low boiling constituents of some crude oils by Rossini and his collaborators.

An attempt only can be made to see how far the application of the graphical statistical methods can be successful in the case of diesel fuels. Supposing that for saturated mixtures with low-boiling constituents the ring-analysis method can be confirmed by ultimate analysis, there still remains the problem as to whether the analysis will enable one to predict some of the practical properties of diesel fuels.

Since the work of Boerlage and the members of his staff (Broeze a.o.)[2] it is known that there exists a close relationship between the ignition quality of diesel fuels and the cetene or cetane number. By comparative work carried out at Delft (Shell group) and Sunbury-on-Thames (Anglo Iranian), it has been proved that in many cases the rating against the primary fuels cetene and α-methylnaphthalene results in very nearly identical cetene numbers.[3]

With the exception of substances like peanut oil, it can be said that in general a tolerance of plus or minus 5 per cent. in cetene numbers can be allowed in practice.

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* This percentage can be calculated from the difference of the aniline point before and after hydrogenation by multiplying it by a certain factor. This factor will not always be constant. (D. J. W. Kreulen, *J. Instn. Petrol. Tech.*, 1937, **23**, 262, compare also below.)

† This method has been investigated, and the results will be published shortly.

‡ For routine-analysis, however, the authors apply such a method to aromatic-free gasoline fractions boiling up to 180° C., the results of which have been shown to be very useful.

Kreulen [4] studied the influence of the composition of gas oils (expressed in percentages of aromatic and naphthenic rings and paraffinic side chains) on the cetene number. From his experiments he derived the formula:

$$\text{Cetene value} = -0{\cdot}2A + 0{\cdot}1N + 0{\cdot}85P,$$

in which A, N, and P represent, respectively, the percentage of *a*romatic rings, *n*aphthenic rings, and *p*araffinic side-chains, of the gas oil, determined by means of the ring analysis method for saturated hydrocarbon mixtures.

By means of this formula he obtained the following results:

TABLE I.

Gas Oil.	Cetene Value, Determined.	Cetene Value Calculated.	Difference.
1	23½	25	+1½
2	35	36	+1
3	37	34	−3
4	41	49	+8
6	51	49	−2
5	51½	54	+2½
11	53	53	0
7	60	52	−8
8	62	60	−2
9	62	63	+1
10	65	61	−4

From the work of Boerlage and Broeze [5] it is known that the molecular ramification has a decided influence on the ignition quality of diesel fuels, since these investigators found that the ignition quality of tetra-*iso*butylene was very low compared with that of *n*-cetene, which has the same empirical formula, $C_{16}H_{32}$.

It was therefore quite reasonable that, although a certain broad relationship between the chemical composition as found by the ring-analysis method and the cetene value exists, there are still other influences which must be considered.

The authors have not at their disposal a large number of data in connection with the relationship between chemical composition and cetene or cetane values. Some data, however, were obtained in 1932 when working with three gas oils (1, 4, and 7); from each of them was derived an Edeleanu raffinate and a hydrogenation product. Nos. 1 and 4 were natural distillates, whereas No. 7 was a cracked product. Therefore No. 7 and the Edeleanu raffinate derived from it (No. 8) contained a certain percentage of olefines. For the investigation Nos. 7 and 8 therefore were first hydrogenated under high pressure with nickel catalyst at low temperature (<100° C.). In this way the olefines were eliminated. The percentage of olefines was calculated from the bromine value, assuming for the olefines the same molecular weight as the mean molecular weight of the gas oil. The hydrogen consumption during the hydrogenation was in accordance with these bromine values.

The content of aromatics (aromatic rings) of the nine gas oils was

calculated *approximately* from the difference of the aniline point before and after hydrogenation by assuming 1° C. increase proportional to 1 per cent. of aromatics.

In Table II is given a summary of the constants of the oils before and after hydrogenation. The specific parachor was not determined because this factor was not used in 1932 for calculating the degree of branching or ramification.[6]

TABLE II.

	Natural Gas Oil, No. 1.			Natural Gas Oil, No. 4.			Cracked Gas Oil, No. 7.		
No.	Original. 1.	Edeleanu Raffinate. 2.	Hydrogenated. 3.	Original. 4.	Edeleanu Raffinate. 5.	Hydrogenated. 6.	Original. 7.	Edeleanu Raffinate. 8.	Hydrogenated. 9.
Properties of the diesel fuels:									
Molecular weight	212	234	213	232	261	229	205	228	221
n_D^{20}	1·5008	1·4733	1·4724	1·4974	1·4628	1·4598	1·4880	1·4541	1·4528
d_4^{20}	0·9002	0·8660	0·8630	0·8801	0·8306	0·8320	0·8632	0·8144	0·8192
$\frac{n^2-1}{n^2+2}\frac{1}{d}$	0·3272	0·3241	0·3247	0·3327	0·3315	0·3291	0·3338	0·3326	0·3298
Aniline point	42·0	70·0	63·6	63·5	86·4	80·6	52·0	76·6	78·4
Bromine value (McIlhiney)	0·2	—	−0·2	1·1	0·5	−0·2	13·8	14·3	−0·4
Cetene value*	37	53	49	53	80	68	61	85	79
Cetane value*	32	46	43	46	70	59	53	74	69
Properties of the completely hydrogenated diesel fuel:									
Molecular weight	218	233	217	236	259	225	208	225	217
n_D^{20}	1·4719	1·4700	1·4663	1·4615	1·4541	1·4560	1·4535	1·4462	1·4506
d_4^{20}	0·8687	0·8627	0·8559	0·8406	0·8218	0·8280	0·8230	0·8059	0·8167
$\frac{n^2-1}{n^2+2}\frac{1}{d}$	0·3223	0·3234	0·3238	0·3267	0·3296	0·3283	0·3287	0·3310	0·3294
Aniline point, °C.	69·6	74·6	70·6	83·4	91·2	84·0	77·2	85·4	80·6
Mean number of rings per molecule	2·0	1·9	1·8	1·4	1·0	1·2	1·1	0·8	1·0
Aniline point increase by hydrogenation	27·6°	4·6°	7·0°	19·9°	4·8°	3·4°	20·1°†	4·0°†	2·2°
Per cent. by wt. of olefines	—	—	—	—	—	—	16‡	20‡	—
Per cent. by wt. of aromatic rings	28	5	7	20	5	3	20	4	2
Per cent. by wt. of naphthenic rings	30	46	45	17	18	29	13	16	26
Per cent. by wt. of paraffinic side chains	42	49	48	63	77	68	67	80	72

* Determined by the Engine Research Laboratory, Bataafsche Petroleum Co., Delft.
† For the olefine-free oil aniline point is taken as 57·1° and 81·4°, respectively.
‡ Calculated from bromine value and from hydrogen consumption at low temperature (<100° C.) hydrogenation.

If we apply Kreulen's formula to the nine diesel fuels it is seen that

the results do not agree with the determined cetene values, the differences are smaller however if the same formula is used for calculating the cetane values.

TABLE III.

Diesel Fuel.	Cetene Value, Determined.	Cetene Value, Calculated.	Difference.	Cetane Value.*	Cetane Value, Calculated.	Difference.
1	37	33	−4	32	33	+1
2	53	45	−8	46	45	−1
3	49	44	−5	43	44	+1
4	53	51	−2	46	51	+5
5	80	66	−14	70	66	−4
6	68	60	−8	59	60	+1
7	61	54	−7	53	54	+1
8	85	63	−16	74	67	−5
9	79	63	−16	69	63	−6

* Corresponding with the determined cetene values.

It would be possible to derive another formula of the same type which would give better agreement with the determined cetene or cetane values. Kreulen determined the specific parachor, but the results cannot explain the differences observed with his gas oils 4 and 7. Moreover, it can be expected also that molecular weight has a marked influence on the ignitability of hydrocarbons of the same class.[7]

The authors are of the opinion that all these considerations make the derivation of a new formula for the correlation between chemical composition and the ignition delay of diesel fuels unnecessary. But what is useless to-day might be very useful in the near future if more data on accurately analysed diesel fuels with known cetene values were available.

If we leave out of consideration the influences of various percentages of different dopes, and if we restrict ourselves therefore to the examination of hydrocarbon mixtures, then the work started by Kreulen is promising. Our own results confirm this opinion.

A more thorough investigation of a large number of diesel fuels in order to study the influence of chemical composition on the cetene or cetane value will be necessary. In this respect it will be advisable to examine a large number of hydrogenated fuels, practically free from sulphur, nitrogen, or oxygen containing bodies, together with extracts and raffinates derived from these fuels, and also oils obtained by polymerising olefines or olefine mixtures.

We are indebted to the N. V. De Bataafsche Petroleum Maatschappij for permission to publish these data.

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DIESEL FUEL CHARACTERISTICS INFLUENCING ENGINE OUTPUT.*

By A. J. Blackwood† and G. H. Cloud.†

It appears to be generally recognized that the small high-speed diesel engine, the rapid development of which has been one of the outstanding engineering accomplishments of the past decade, still lacks the ability to digest the broad variety of fuels on which its slow-speed predecessors seemed to thrive.

Inasmuch as fuels vary in quality, depending on many factors, including crude source and method of processing, the engine manufacturer is faced with the problem of reducing the fuel sensitivity of his high-speed engine so that customer acceptance may not be limited. His problem is serious, because there is as yet no widely standardized pattern for high-speed diesel fuels such as exists for gasoline.

It happens not infrequently that engines are built and then experimentally tested on fuels available at or near the engine manufacturer's plant. The engines may perform satisfactorily on the fuel used. Later, when placed in the customer's hands in different parts of the world, a multitude of troubles often develop due to the wide differences in the various fuels sold for the engine.

Numerous engine-design features and mechanical devices have helped to alleviate this handicap, since they tend to eliminate the necessity for "tailor-made" fuels. At the same time, the refiner is also concerned in engine-design trends, because if the fuel sensitivity of the engine is reduced, then the widespread availability of suitable products becomes increasingly feasible from the economic viewpoint. It is thus readily apparent that co-operation between the two interests will aid greatly the development and use of the small high-speed power plant.

There are many pressing diesel fuel problems on which the engine-man and the fuel technologist can advantageously co-operate, and there is increasing evidence that each is beginning to realize that, while he may be hard pressed to reach a solution of immediate problems of his own, it may pay dividends to have a sympathetic look at the other fellow's kindred problem and work co-operatively towards a mutually satisfactory solution.

This paper is very largely a study of data obtained on a programme of tests intended to provide information on questions of importance to engine-builder, fuel-supplier, and the oft-forgotten man—the customer. No attempt will be made to analyse such problems as cold starting, smoking, roughness, odour, or engine deposits. Rather an analysis of those fuel factors influencing principally power and fuel economy will be attempted. In order to study the effects of a large number of physical and chemical fuel characteristics on engine performance, as well as to be able to permit a dissociation of the separate effects due to any one particular characteristic,

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† Standard Oil Development Co.

a group of gas oils selected from widely different crudes were each fractionated into four cuts of 100° F. boiling range. This provided a series of some thirty samples, to which have been added numerous commercial fuels. It should be realized that the special cuts are impractical commercially and of interest only from a research viewpoint. All inspection data that might seemingly affect engine-performance characteristics were determined on each of the original gas oils and on each cut, and although these inspections are not included in this paper, they form the basis of correlations which are presented. It would be an enormous task to present the entire mass of original data together with the interpretation of the engine results. For this reason, it has seemed desirable in most cases to present "cross-plotted" data on final results only, rather than to give the detail development and original data.

The various fuels have been run in a variety of engines from time to time, although the most complete set of data has been obtained on a six-cylinder, $3\frac{1}{4} \times 4\frac{1}{4}$, ante-chamber engine capable of running up to about 2600 r.p.m. Considerable data were also obtained on a C.F.R. diesel engine attached to an electric dynamometer. Tests were run covering a wide variety of test conditions, and a study has been made of the relationships between performance and fuel properties, particularly with respect to the factors influencing power and economy. With a variety of fuels covering such a wide range of ignition quality, boiling range, and gravities, groups of samples can be selected which have certain characteristics in common, and these studied as being independent of other variables.

From strictly practical considerations, and to simplify the selection of that part of the complete data suitable for this paper, the multi-cylinder engine results which are presented are very largely those obtained when operating at combinations of load and speed which correspond to the conditions of driving a vehicle on a level road at the speeds designated. In this way, fuel consumptions are comparable generally with those realized in service, and the variations due to the fuel properties discussed have a practical application.

It may be well at this point to emphasize an important consideration which is very frequently overlooked in analysing fuel-consumption data. Engineers have been trained to evaluate engine efficiency in terms of pounds of fuel per horse-power hour. From a heat-efficiency standpoint, this is sound, since the heat content of fuels on a pound basis does not change very much with other properties. On the other hand, fuels are sold on a gallonage basis, and there is an appreciably greater number of B.T.U.s in a gallon of low-A.P.I. (*i.e.*, high-specific) gravity fuel than in a gallon of high-A.P.I. (low-specific) gravity fuel. For example, a gallon of 30-A.P.I. gravity fuel (sp. gr. = 0·876) may contain 6–8 per cent. more B.T.U.s than a gallon of 50-gravity fuel (sp. gr. = 0·78). So long as fuels are sold on a volume rather than a weight basis, this is the important thing from the user's viewpoint, and it is for this reason that volumetric fuel economy is used in this paper. The following short table of data for road–load conditions is presented to illustrate this point, since it is not uncommon to find diesel engineers and operators who express strong preferences for the fuel which is most efficient in their engine on a basis of specific fuel consumption in pounds per horse-power per hour.

	Pounds of Fuel per Brake Horse-power per Hour.	U.S. Pints of Fuel per Brake Horse-power per Hour.*
Fuel A. . .	0·577	0·672
Fuel B. . .	0·580	0·660
Fuel C. . .	0·585	0·653

* 1 Imp. Gallon = 1·2 U.S. Gallons.

Fuel A is the best of the three fuels on a weight basis, showing about 1·4 per cent. better fuel consumption, and the normal tendency would be to select this fuel as the best of the three. Actually, however, the customer would be losing money by buying Fuel A, since for the same power output on a volume basis Fuel C would give about 3 per cent. lower consumption. It might be, of course, that operation at high speeds would not be satisfactory on the heavier, lower-cetane-number fuel, in which case the selection of Fuel A would be justified. This phase of the problem will be covered in more detail in the discussion on effect of ignition quality.

Effect of Fuel Volatility.

Although a discussion of the importance of fuel-ignition quality might logically come first on the list of fuel properties, it seems more desirable to discuss briefly the effect of fuel volatility. Unlike the gasoline engine, where the fuel is mixed with the air in a carburettor and delivered through a manifold to the various cylinders, the diesel has its fuel injected directly into the combustion chamber, and it would not be anticipated that the volatility of the fuel, unless carried to extremes, would have any great influence on power or economy. This, of course, assumes that the fuel burns properly when sprayed into the hot air in the combustion chamber. The effect of fuel volatility at moderate speed (1500 r.p.m.) and corresponding road load is illustrated in Fig. 1, which, under these particular conditions, shows the relation of mid-boiling point to specific consumption in U.S. pints per brake horse-power hour for fuels of constant gravity and ignition quality. Results at increasing speeds with the same injection setting show a similar relation between mid-boiling point and consumption. For constant cetane number, then, the volumetric fuel economy improves with increasing mid-boiling point, which, as will be shown later, is no doubt due to the fact that, for either constant gravity or cetane number, an increase in mid-boiling point of a fuel is accompanied by a corresponding increase in heating value per gallon. However, it is generally true that the customer will obtain better fuel mileage on high-boiling fuels provided the engine can efficiently burn them. This depends on the type of engine, speed of operation, and cetane number of the fuel.

Effect of Ignition Quality.

A great deal has been said and written concerning the importance of ignition quality of diesel fuels. Boerlage and Broeze were among the first to study the ignition delay characteristics of diesel fuels, and they proposed a method of evaluating this delay property by means of matching the

FIG. 1.

EFFECT OF VOLATILITY FOR FUELS OF CONSTANT CETANE NO.
(Road Load. 1500 r.p.m.)

EFFECT OF VOLATILITY FOR FUELS OF CONSTANT GRAVITY.
(Road Load. 1500 r.p.m.)

unknown fuel with a blend of two primary reference fuels in much the same general way that gasolines are evaluated for anti-knock.[1] From this early work has developed the present system of expressing ignition quality in terms of cetane number. There is no doubt that ignition quality has received more attention and study than any of the other fuel characteristics which affect engine performance, and it is still considered by many to be of the utmost importance. Nevertheless, there still remains considerable doubt as to the influence of ignition quality *per se* when stripped of other fuel property influences, since it is believed that insufficient work has been reported in the literature to demonstrate definitely the importance of cetane number or to obtain a clear distinction between the effect of cetane number and other fuel properties. The engine performance on the special cuts prepared for the work being described provided an opportunity to study some phases of this important question. It might be assumed, for example, from the preceding discussion on fuel volatilities and from the curves in Fig. 1, that fuel economy is impaired by going to high-cetane-number fuels. This is not always the case when economy is expressed on a volumetric basis, and probably not ever the case when it is expressed on a pound basis. A consideration of the data presented in Figs. 1, 2, and 4 will clarify the latter statement. For example, consider in Fig. 1 (left) two fuels of 600 mid-boiling point, one of 30 cetane number and the other of 70 cetane number. The physical properties read from Fig. 4 indicate that the first fuel will have a heat content of 148,000 and the second fuel a heat content of 138,000 B.T.U. per U.S. gallon. The ratio of these heat contents is 1·07, whereas the ratio of the pints per brake horse-power hour is 1·06, indicating that the change in economy with cetane number is the result of the change in heat content. Consider another pair of fuels on Fig. 1 (left), both of 50 cetane number, one of 700 mid-boiling point and the other of 450 mid-boiling point. The physical properties as read from Fig. 4 show that these have heat contents of 144,000 and 136,000 B.T.U. per U.S. gallon, the ratio of which is 1·05, which compares with a ratio of 1·05 for the indicated experimental economies. The same interrelation exists on any pairs of fuels chosen on Fig. 1, either left or right. However, changes in fuel economy are not invariably due to differences in heating value, as is shown by Fig. 2, which gives the relation between the consumption, gravity, cetane number, and r.p.m. On Fig. 2 by the dotted lines have been indicated the change in consumption with cetane number which would occur if heat content were the only influence. In each case the 47·6-gravity fuel has been taken as a basis. It will be noted, in the lower curve represented by 1500 r.p.m., that the consumption is directly proportional to the heat content, whereas when speed is increased and ignition lag more important, consumption deviates from the heat-content basis in favour of cetane number. It appears, therefore, that there is an optimum balance between heat content per gallon, cetane number, and speed. In other words, under relatively low-speed conditions, where quickness of ignition is of secondary importance, the best consumption is obtained on the fuel of highest heating value, whereas at high speeds, under conditions where quick ignition is imperative and where the quality of the combustion might logically be expected to influence output more than at low speeds, the fuel of superior ignition quality gives fuel economies which may readily exceed

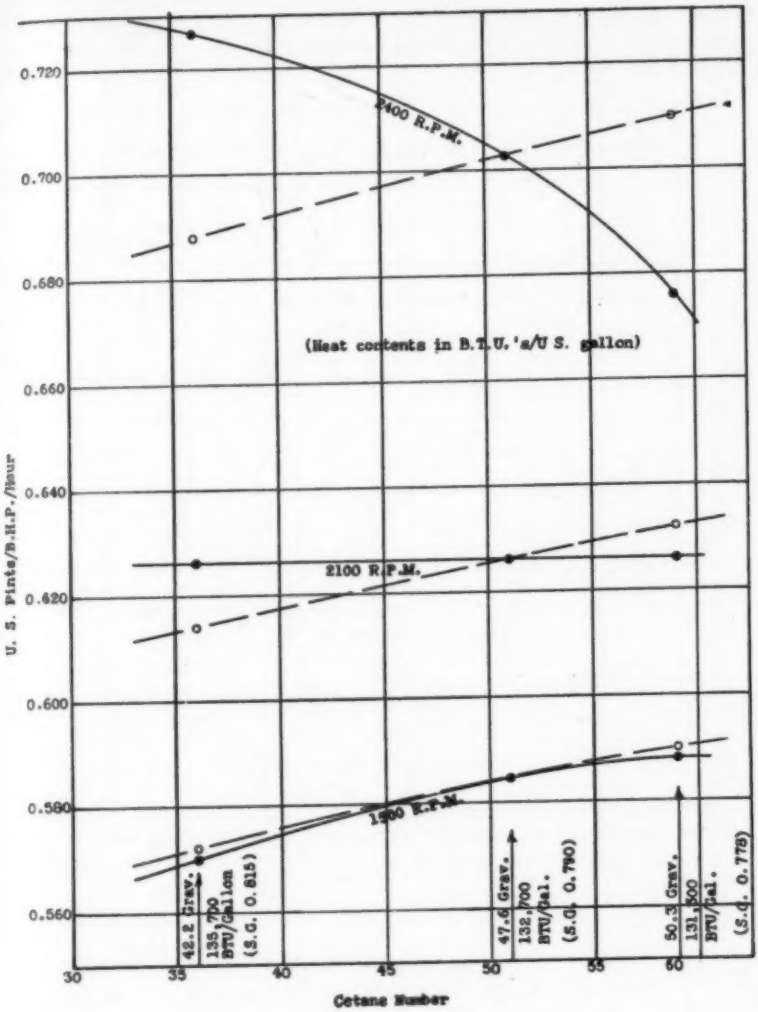


FIG. 2.

EFFECT OF GRAVITY AND IGNITION QUALITY ON FUEL CONSUMPTION FOR FUELS OF SIMILAR VISCOSITY AND VOLATILITY.

(The dotted lines show how volumetric fuel economy would change if dependent only upon B.T.U./Gallon—based on the 47·6 gravity fuel.)

those attained on fuels of higher heat content but poorer ignition quality. It may be that, on engines having provision for varying injection timing and rate of injection, even greater advantage may be realized from fuels of high ignition quality.

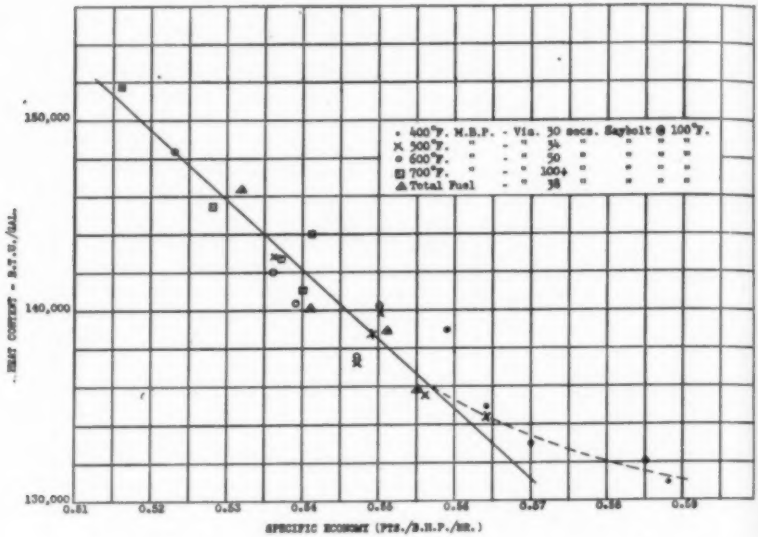


FIG. 3.

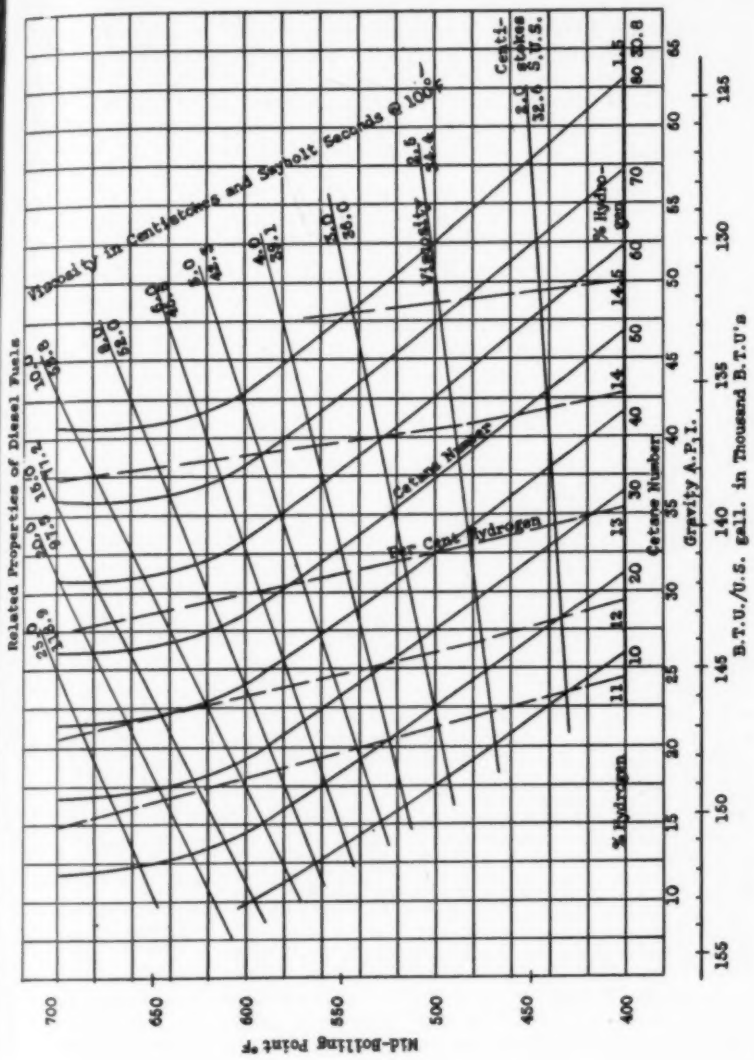
HEAT CONTENT (B.T.U.'S/U.S. GALLON) *v.* VOLUMETRIC ECONOMY (U.S. PINTS/B.H.P. PER HOUR.)

6-CYLINDER ANTECHAMBER ENGINE.

(Road Load. 1500 r.p.m.)

Engine-power is likewise affected by ignition quality in a way similar to fuel economy, as might be expected. The following table of data illustrates this point for two fuels having fairly wide differences in ignition quality.

	Fuel Properties.		Power Output.			
			800 r.p.m.		2100 r.p.m.	
	Fuel A.	Fuel B.	Fuel A.	Fuel B.	Fuel A.	Fuel B.
Gravity, ° A.P.I. . .	33·3	37·9	27·3	24·5	64·0	66·8
Specific gravity . .	0·859	0·835				
Cetane number . .	43·7	67·8				
Pounds/U.S. gallon .	7·15	6·96				
B.T.U./U.S. gallon . .	140,500	137,800				
B.T.U./pound . .	19,650	19,800				


Related Properties of Diesel Fuels
Viscosity in Centistokes and Saybolt Seconds @ 100° F
Cetane Number
Per Cent Hydrogen
Mid-Boiling Point °F
Gravity A.P.I.
Cetane Number
% Hydrogen
Viscosity
Centi-stokes
S.V.S.
% Hydro-gen
B.T.U./U.S. gall. in Thousand B.T.U's
700
650
600
550
500
450
400
155
150
145
140
135
130
125
65
60
55
50
45
40
35
30
25
20
15
10
5
80
70
60
50
40
30
20
13
12
11
10
2.0
32.6
2.5
34.4
3.0
30.0
4.0
29.7
5.0
40.0
6.0
43.0
8.0
52.0
10.0
66.0
20.0
91.5
16.0
71.2
25.0
118.9
1.5
30.8
14.5
14

Although Fuel A has about 2 per cent. higher heating value per gallon and delivers some 11 per cent. more power at 800 r.p.m. than does Fuel B, the situation is reversed at 2100 r.p.m., where Fuel B develops between 4 and 5 per cent. more power than Fuel A. Evidently, under the conditions of these tests, the combustion of low-ignition-quality fuels is not efficient at high speeds, and conversely the high-ignition-quality fuel is not as efficiently burned at low speeds. This would probably have been reflected in a corresponding change in the fuel economy shown in Fig. 2 if tests at low speeds had been included.

Effect of Fuel Viscosity.

There is considerable difference of opinion among diesel technologists as to the effect of viscosity on performance. Many diesel engineers are concerned about viscosity from considerations of wear on pump and injector parts. The petroleum technical people, in addition to fears about wear, are perhaps fully as concerned about power and economy as affected by viscosity. Obviously viscosity is difficult to dissociate from other fuel properties, and it is this aspect of the viscosity question with which this paper deals.

Messrs. Rothrock and Marsh of the N.A.C.A.[3] found that with a new, commercial, fuel-injection pump the rates of fuel injection showed little variation for a range of fuel viscosities from that of gasoline to that of an S.A.E. 30 lubricating oil. Le Mesurier has stated [4] that fuel consumption appears to be quite independent of viscosity except where leakage exists in the fuel system due to badly worn injection equipment. He observed that the leakage increases rapidly with decreasing viscosity, the reciprocal of the leakage (by weight) plotted against kinematic viscosity giving a straight-line relationship except at very low viscosities.

There is evidence to indicate that, with worn injection equipment, fuels of low viscosity show a loss in power in cases where engines are equipped with throttle stops or governor stops to prevent overload. In such cases, in addition to the lower-viscosity fuels having lower heating value per gallon, the full fuel delivery simply does not reach the combustion chamber, and the net power loss is due to the combined effect. The petroleum field-engineer meets cases, particularly in tractor operations, where low-viscosity fuels produce severe power losses in worn equipment and trade may be lost simply because a competitor may have a higher-viscosity fuel.

In general, it would appear from the data in the literature, and from considerations of flow as a function of clearance and viscosity, that two broad conclusions can be reached, namely :—

(*a*) An increase in viscosity from 33 to 40 seconds Saybolt (2·1–4·2 centistokes) at 100° F. cuts the leakage in half.

(*b*) Doubling the pump clearances increases the leakage fourfold. In other words, good mechanical condition of the pump is the cure for troubles caused by leakage rather than increase in viscosity of the fuel.

A study of fuel consumption covering a wide range of fuel viscosity has been made on a 6-cylinder antechamber-type engine having injection equipment in good condition. The results were plotted as functions of

several fuel characteristics, with the result that, by and large, the fuel consumption seemed to correlate best with heating value of the fuel, as might be expected, with viscosity having only minor influence. Fig. 3 is a plot of the data, showing the relation between fuel consumption in the 6-cylinder engine at 1500 r.p.m. and road load and heating value in B.T.U.s per U.S. gallon. Except for very low viscosity fuels, as indicated by the broken line through the solid dots, the points show a linear relationship. The low-vicosity fuels show somewhat higher consumption than might be expected from heating values. These results were obtained at 1500 r.p.m., which is in the speed range where—as previously shown for this same engine—ignition quality had but slight effect on fuel economy, and in this plot there is no evidence to indicate that the deviations from the average line are due to ignition quality differences. It may be that the accuracy of determining heating values could account for the deviations from the line, but it is unlikely that this could also account for the relatively poor economy of the very low-viscosity fuels.

Effect of Gravity and Heating Value.

Gravity has not generally been considered an important property of a diesel fuel. However, since fuels are sold on a volume basis, and since gravity is in an approximate way a measure of the heat content of a fuel in B.T.U.s per gallon, it follows that relative gravities should be reasonably good indices of the volumetric economy obtainable from various fuels when the fuel is burned to best advantage. For fuels generally suitable for high-speed diesel engines, a decrease of 2·5° A.P.I. gravity (*i.e.*, an increase in specific gravity of 0·01 approximately) corresponds approximately to an increase of 1 per cent. in heating value, which in turn will usually be reflected in an increase of 1 per cent. in fuel economy. This, of course, does not hold for high-speed operation, where differences in cetane number of the fuels being compared may change this relationship, as has already been demonstrated in the preceding sections.

At present the trend in the U.S.A. appears to be towards volatile, highly-paraffinic fuels which necessarily have high-A.P.I. (low-specific) gravity. It may be, when the various engine manufacturers have overcome the smoking and engine-fouling troubles that have prompted the demand for lighter fuels; and when diesel engines are purchased on a basis of the fuel economy possible with one engine compared to another, rather than as compared with a correspondingly powered gasoline engine as at present, that more attention will be given by the engine-builder to fuel economy. This will probably result in a demand for fuels of higher heat content per gallon—*i.e.*, higher-specific-gravity fuels. Just how far the trend in engine speeds and the ability to use low-cetane-number fuels will permit this to extend remains to be seen.

In reviewing the various phases of engine operation which have been discussed, it is apparent that of all the fuel characteristics which seemingly influence engine power and economy, only heating value, ignition quality, and possibly viscosity are basically important. Since this is the case, it would be convenient to have as a reference chart a set of curves showing the interrelation of the important fuel properties. For this purpose,

Fig. 4 has been prepared, this chart being similar in many respects to that of Watson, Nelson, and Murphy,[5] but expanded to include more variables. Knowing two characteristics to locate a point on this chart, the other fuel properties can be ascertained, and their importance evaluated. In this chart, heating value, B.T.U. per U.S. gallon, is shown as directly related to gravity, which is not strictly accurate, since for the same gravity hydrogen content does affect heat of combustion to a degree. A chart of this kind can be of immeasurable help in learning to appreciate the significance of the interrelated fuel properties. It is also of assistance in setting limits of fuel properties when writing specifications such that "impossible" requirements are not established as frequently happens.

In conclusion, the points which seem to be of greatest significance may be summarized as follows :—

1. Fuel viscosity *per se* is not a major factor in the power performance of high-speed diesel engines, except in instances where worn injection equipment might make it undesirable to use a low-viscosity product.

2. Assuming complete combustion, fuel volatility affects fuel economy only as it is related to heating value and ignition quality. Heating value, in terms of B.T.U. per gallon, may be closely estimated from gravity.

3. For most present-day engines having fixed injection timing, ignition quality is a major factor in determining economy in the upper speed ranges. At the lower engine speeds, heat content, as measured by B.T.U. per gallon, or as estimated from gravity, is the most important consideration in economy.

4. The principal diesel-fuel characteristics—viscosity, mid-boiling point, gravity, hydrogen content, heating value (B.T.U. per gallon), and cetane number—are very closely related. If any two of these are known for a given fuel, the others can be closely estimated from a chart such as presented in Fig. 4.

Suggested Reading.

[1] *Automotive Industries*, 1932, **67**, 79
[2] H. N. Bassett, *Automotive Engineer*, January 1937, p. 21.
[3] A. M. Rothrock and E. T. Marsh, *N.A.C.A. Report*, 1934, No. 477.
[4] Le Mesurier, *J. Instn Pet. Tech.*, 1931, **17**, 397.
[5] *Ind. and Eng. Chem.*, 1935, **27**, 1460.
[6] *Ibid.*, 1935, **27**, 152.
[7] R. D. Best, *Nat. Petrol. News*, 1937, **29**, No. 40-R-232-6.
[8] R. F. Selden, *N.A.C.A. Report*, 1938, No. 167.

EVALUATION OF CERTAIN NORMAL ALKYLATED BENZENES AS DIESEL FUELS.

By GANN SHEN, B.Sc., C. E. WOOD, M.Sc., F.Inst.Pet. and F. H. GARNER, Ph.D., F.Inst.Pet.

INTRODUCTION.

THERE has been no systematic investigation of the ignition quality of pure hydrocarbons distilling within the diesel fuel range, although the octane numbers of a large number of pure hydrocarbons in the gasoline range have been determined.* The hydrocarbons investigated include paraffin hydrocarbons, unsaturated aliphatic hydrocarbons, aromatic hydrocarbons, saturated naphthene hydrocarbons, with both five and six rings, in addition to a number of unsaturated naphthene hydrocarbons and a certain number of dienes.

As regards hydrocarbons in the diesel fuel range, Boerlage and Broeze suggested the use of mixtures of cetene and mesitylene for the rating of diesel fuels.† These have more recently been replaced by cetane and α-methylnaphthalene, and the percentage of cetane in the blend is the cetane number of the fuel. In the paper by Boerlage and Broeze, figures are quoted for blends of tetra*iso*butylene with a gas oil of 70 cetene number, but these five hydrocarbons appear to be the only pure hydrocarbons of which the ignition quality has been investigated.

In 1932, Ormandy,‡ pointed out the analogy between the use of gas oil for gas-works practice and gas oil used as diesel fuels, and that it was desirable to use diesel fuels which cracked readily. The thermal stability depends on the molecular structure and, as pointed out by Boerlage and Broeze, straight-chain paraffin hydrocarbons are the least stable. The molecular structure of a fuel is the deciding factor in ignition quality; aromatic rings are fairly stable, and likewise paraffin hydrocarbons with branched side-chains. Cracked diesel fuels tend to have poorer ignition quality than straight-run fuels, depending on the intensity of cracking. Dumanois § suggested the use of heptane value as a method of expressing the ignition quality of diesel fuels, and this would be determined in the standard C.F.R. gasoline engine by the procedure used in the determination of octane numbers, but expressed in percentage heptane instead of percentage octane. The fuel used was to be blended with gas oil in the ratio of 15 : 85. There is at least a general relationship between heptane values determined in this way and cetane numbers determined in the diesel engine, as paraffin hydrocarbons are satisfactory for compression-ignition engines but unsatisfactory for spark-ignition engines, whereas the reverse is the case with aromatic hydrocarbons.

In the present investigations it was decided to determine the cetane numbers of a number of hydrocarbons derived from benzene by increasing

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* W. G. Lovell and J. S. Campbell, "Science of Petroleum," **4**, 3004.
† *Transactions S.A.E.*, 1932, **27**, 283.
‡ *J. Instn. Petrol. Tech.*, **18**, 576. § *Compt. rend.*, 1933, **196**, 1003.

the length of the paraffinic side-chain. Normal amylbenzene distils over at 204° C., and this is within the distillation range of diesel oils. The other three hydrocarbons investigated—normal hexyl, normal heptyl, and normal nonyl—also come within the distillation range of the lighter and middle fractions of diesel oil, as the normal nonylbenzene boils at 280° C.

Evaluation of Diesel Oil by Engine Tests.

Le Mesurier and Stansfield in 1931 measured the delay angle on a series of fuels with the help of a Farnborough indicator, and also determined ease of starting by adjusting the temperature of both jacket and air until the temperature was sufficiently low that hesitation occurred before firing commenced.*

Boerlage and Broeze described work † in which they had carried out tests on the ignition quality of fuels of compression-ignition engines, and in this paper the original suggestion was made that cetene and mesitylene should be used, as standards, for measuring the ignition quality of fuels. Indicator diagrams (out of phase) were taken on a Miahak indicator, which proved to be sufficiently accurate for the first stages of combustion, as was shown by correlation with an optical indicator. The test engine used was an adapted Thomassen 20-h.p. engine which was run at 100–350 r.p.m. at light load. A critical compression ratio (C.C.R.) method was introduced by Pope and Murdock; ‡ these tests were conducted on a standard C.F.R. engine converted for compression-ignition operation. The engine is motored without injection of fuel at a known compression ratio under specified conditions, and fuel is then injected for three seconds. Should an audible combustion be heard at the exhaust within this time, the compression ratio is lowered and the procedure is repeated. The lowest compression ratio at which combustion occurs is the critical compression ratio. The lower the critical compression ratio, the better is the ignition quality of the fuel.

The present standard methods which have been put forward for the determination of cetane numbers are those by the Institute of Petroleum and the A.S.T.M. In I.P.T. Serial Designation FO.39.T, the ignition quality is expressed as cetane number. Two reference fuels, I.P.T. high-ignition quality (70·5 cetane number), and I.P.T. low-ignition quality (18 cetane number), are used, and it is stated that it has not been found necessary to standardize any particular engine for the determination of ignition quality, although an engine of high-compression ratio with constant spray valve opening time and steady ignition characteristics must be used. There is, however, some evidence that the cetane number of both high- and low-ignition-quality fuels may show finite differences when tested on widely different types of engines. The A.S.T.M. has published (in October 1938), for information, a proposed method of test for the ignition quality of diesel fuels, and in this method the standard C.F.R. diesel engine is used, the delay angle being fixed at 13° and the cetane number determined from the compression ratio. A high cetane secondary reference fuel made from petroleum is prescribed, but the low-cetane secondary reference is a mixture of α- and β-methylnaphthalene.

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* *J. Instn. Petrol. Tech.*, 1931, **17**, 387.
† *Engineering*, 1931, **132**, 603, 687 and 755.
‡ *J. Soc. aut. Engrs*, 1932, **30**, 136.

In the present investigation a C.F.R. diesel engine was employed, to which the Schweitzer and Hetzel apparatus was fitted, so that in the cetane number determination the ignition delay angle could be adjusted to a constant figure of 13° crank-angle.

Hydrocarbons Used in this Investigation.

As already mentioned, very little research has been done on pure hydrocarbons within the distillation range of diesel fuels, and for this research it was decided to select compounds having properties intermediate between aromatic and paraffin hydrocarbons. Although straight-chain paraffin hydrocarbons are present in diesel fuels, the proportion is necessarily small, owing to the necessity of the diesel fuel used having a satisfactorily low pour point. From the investigations made at the Bureau of Standards it appears that substituted aromatic hydrocarbons are present in lubricating oils, but little work has been done on the isolation of individual hydrocarbons present in the diesel-oil fractions of crude petroleum.

Normal monoalkylated benzenes were the compounds chosen as most suitable for this initial investigation, compounds in which the aromatic influence is gradually diminished. A series of normal alkylated benzenes ranging from normal *n*-amyl to *n*-nonyl were prepared on which the following problems could be studied :—

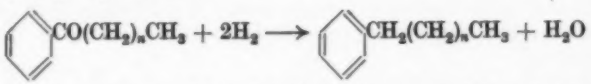
(1) The effect on ignition quality of increasing the length of a paraffin side-chain.

(2) A comparison between the effect of ignition quality on a paraffin and aromatic nucleus, since the number of paraffinic carbon atoms in the side-chain varies from 4 to 9, as against 6 in the aromatic nucleus.

(3) The validity of purely physical tests for evaluating the ignition quality as determined in the engine for this type of hydrocarbon.

Preparation of Hydrocarbons.

Normal monoalkylated benzenes were prepared by reducing the corresponding alkyl aryl ketones.



the ketones being obtained by acylation of benzene with acyl chlorides by means of Friedel and Crafts' reaction. Two methods were employed for their hydrogenation :—

(1) Clemmensen's method of reduction by means of zinc amalgam and hydrochloric acid.

(2) Catalytic hydrogenation of the ketone in alcoholic solution under a pressure slightly greater than atmospheric in the presence of palladium deposited on animal charcoal.

The following data briefly summarize the physical properties of the alkylbenzenes under consideration as determined by us on the principal hydrocarbons.

Hydrocarbon.	Boiling Pt. ° C.		Viscosity Centistokes.		Specific Gravity. 60° F.
	9 mm.	760 mm.	100° F.	210° F.	
n-Amylbenzene . .	77–78	204–205	1·2260	0·6605	0·8662
n-Hexylbenzene . .	93–94	226–227	1·4647	0·7527	0·8646
n-Heptylbenzene .	108–109	240–241	1·7845	0·8632	0·8637
n-Nonylbenzene . .	137·5–138·5	280–281	2·4501	0·1060	0·8626

Aniline Point.

All these alkylbenzenes are miscible with aniline in equal volumes even at — 10° C.

Determination of the Cetane Number.

The engine tests were carried out in the Esso European Laboratories at Vauxhall by Mr. A. Prizeman.

Method of Rating.

The tests were made on the C.F.R. diesel fuel-testing engine. Fixed-ignition lag method was adopted which was developed by Hetzel and Schweitzer.* Due to the uncertainty and difficult controlling of the bouncing pin, an electric magnetic unit, such as is used in the magnetic type of radio speakers, is employed in this method. A short stiff wire resting on the diaphragm transmits the motion to the armature of the unit. The current generated in the coil surrounding the armature reduces the negative voltage on the grid of a thyratron tube, thereby causing it to conduct. The current passing to the plate of the tube goes to a high-tension coil, which in turn sends a flash through the neon lamp. During ignition, the velocity of the diaphragm is high, thus the thyratron relay trips and causes the neon lamp to flash. Instead of using an ordinary protractor, the neon lamp is mounted on the fly-wheel, which has a larger scale and permits the operator to read the angles accurately and conveniently in a standing position.

During the tests, the engine was operated under the following standardized conditions :—

(*a*) Engine speed, r.p.m. 900.
(*b*) Jacket-water temperature, 210° F.
(*c*) Air inlet temperature, 140° F.
(*d*) Lubricating oil temperature, 110° F.
(*e*) Injection pressure (valve opening pressure) lbs./in.^{2}, 1500.
(*f*) Fuel quantity, c.c. per minute, 13.
(*g*) Injection advance angle, 13 degrees.
(*h*) Compression ratio varied until ignition registered at top dead centre as indicated by the neon lamp flash, *i.e.*, delay angle fixed at 13 degrees.

* *J. Soc. aut. Engrs*, 1936, **38**, 206; *Automotive Industries*, 17th August, 1935, **73**, 202.

Two reference fuels, the I.P.T. high-ignition-quality and low-ignition-quality secondary reference fuels, were used to match the sample. The high standard fuel had a cetane number of 70·5 and the low standard, cetane number 18. Fuels of any cetane number between 70·5 and 18 can be matched by mixing these two reference fuels.

The cetane number of a fuel is determined by comparing its compression ratio (read from the micrometer reading) with those for various blends of the reference fuels; two blends are found which differ in compression ratio by not more than the equivalent of 8 cetane numbers, one of which has a higher and the other a lower cetane number than the sample of fuel.

Results are reproducible within $\pm$ 1 cetane number by careful operation. The following table shows the cetane numbers of the hydrocarbons and blends of the hydrocarbons with light reference fuels.

Hydrocarbon.	Cetane numbers. % by volume of hydrocarbon in high standard reference fuel.			
	100%.	60%.	50%.	20%.
n-Amylbenzene	—	38	42	—
n-Hexylbenzene	26	—	52	63
n-Heptylbenzene	35	—	54	64
n-Nonylbenzene	50	—	60	66

n-Amylbenzene could not be run straight in the engine.

The percentages by volume are converted to percentage by weight. The specific gravities of the high standard reference fuel is 0·8070 at 60° F.

Hydrocarbon.	% by weight hydrocarbon.	% by weight high standard reference fuel.	Cetane no.
(1) *n*-Amylbenzene . . .	100	—	—
	51·8	48·2	42
	61·6	38·4	38
(2) *n*-Hexylbenzene . . .	100	—	26
	21·1	78·9	63
	51·7	48·3	52
(3) *n*-Heptylbenzene . . .	100	—	35
	21·1	78·9	64
	51·7	48·3	54
(4) *n*-Nonylbenzene . . .	100	—	50
	21·1	78·9	66
	51·7	48·3	60

Discussion of Results.

(1) Boerlage and Broeze * found that cetene numbers, when expressed in weight instead of volume percentage, were additive, so that cetene numbers of fuel blends showed a linear relationship. If this applies to cetane numbers of blends, the cetane number of the unblended pure hydrocarbon could be read off by extrapolation of a graph showing cetane number

* *J. Soc. aut. Engrs*, 1932, **27**, 289; "Science of Petroleum," **4**, 2493.

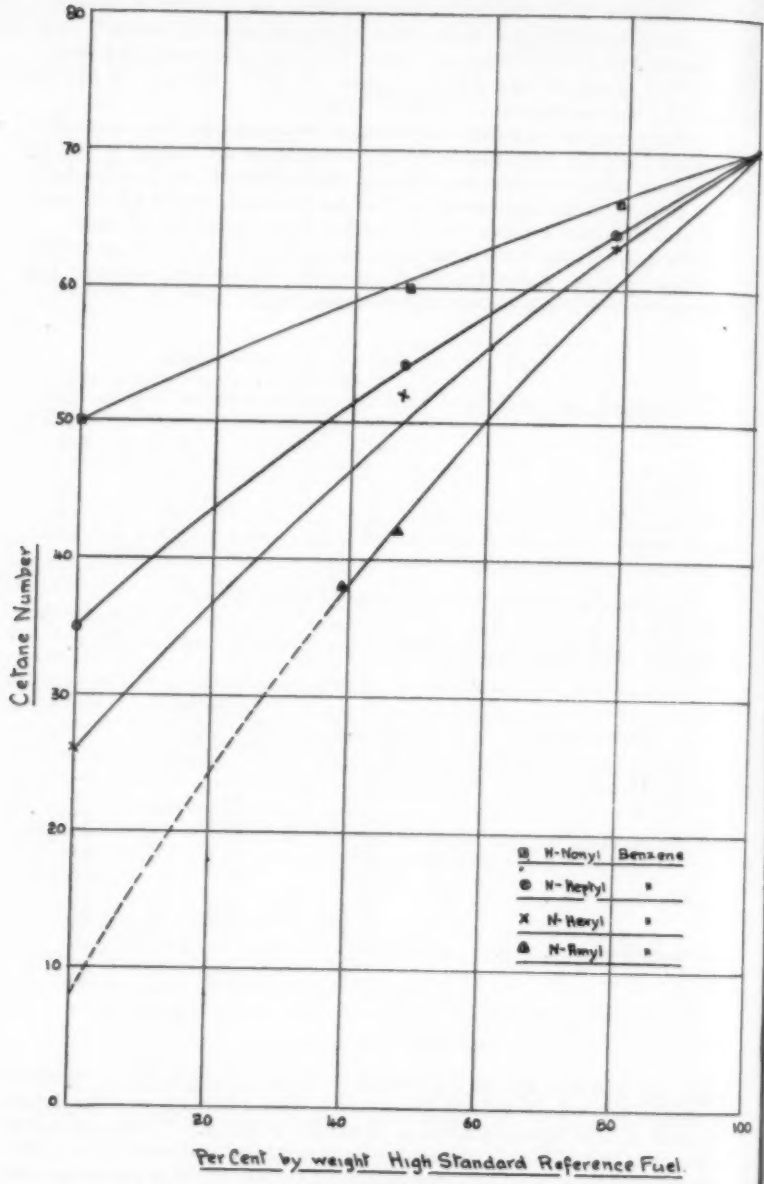

Cetane Number
0
10
20
30
40
50
60
70
80
20
40
60
80
100
Per Cent by weight High Standard Reference Fuel
n-Nonyl Benzene
n-Heptyl "
n-Hexyl "
n-Amyl "

FIG. 1.

against percentage by weight of the high-ignition quality of secondary reference fuels. The experimental results, which are given in Fig. 1, show that the lines representing the cetane numbers of blends of high reference fuel and of the pure hydrocarbons are curved in all cases, with the possible exception of normal nonylbenzene; the curvature becomes greater the lower the molecular weight of the hydrocarbon.

The following table shows the blending cetane number of the four hydrocarbons calculated from the 50 per cent. point shown on Fig. 1.

n-Nonylbenzene . . .	51
n-Heptylbenzene . . .	39
n-Hexylbenzene . . .	32
n-Amylbenzene . . .	18

Fig. 2 shows actual and blending cetane numbers of the pure hydrocarbons. The actual cetane numbers are those experimentally determined for *n*-nonylbenzene, *n*-heptylbenzene, and *n*-hexylbenzene, together with that extrapolated from the blending curve shown in Fig. 1 for *n*-amylbenzene. It will be seen from Fig. 2 that the blends of high cetane reference fuel with the individual aromatic hydrocarbons investigated have cetane numbers which are always higher than would be anticipated from their percentage composition.

(2) The cetane numbers of the alkylated benzenes increase with increasing number of carbon atoms in the side-chain. Whereas amylbenzene with a cetane number of about 8 shows the poor ignition quality found in aromatic hydrocarbons, with increasing length of side-chain the cetane numbers improve quite rapidly. The cetane number of 50 for *n*-nonylbenzene is higher than would be anticipated from this hydrocarbon.

(3) Aniline point has no significance in the evaluation of this particular type of hydrocarbon, since the aniline points of all four alkylbenzenes are below $-10°$ C.

Similarly the following table shows the cetene number calculated by Moore and Kaye's formula * from the viscosity/gravity constant, together with the cetane number as calculated from the experimental cetene number. This formula is as follows :—

$G = 1{\cdot}082A - 0{\cdot}0887 + (0{\cdot}776 - 0{\cdot}72A)[\log\log(KV - 4)]$ where G = sp. gr. at 60° F.

A = modified viscosity/gravity constant.

KV = kinematic viscosity in millistokes at 100° F. Cetene number can be calculated from the following equation :—

$A = 1{\cdot}015 - 0{\cdot}003N$, where N = cetene number.

Hydrocarbon.	Modified V.G.C.	Calculated cetene number.	Determined cetene number.
n-Amylbenzene . . .	0·9933	7·3	10 †
n-Hexylbenzene . . .	0·8795	43·8	30
n-Heptylbenzene . . .	0·8725	47·5	40
n-Nonylbenzene . . .	0·8623	50·8	57

* Moore and Kaye, *Oil Gas J.*, Nov. 15, 1934, 108.

† These figures are calculated from the relationship—70 cetane numbers are equivalent to 80 cetene numbers.

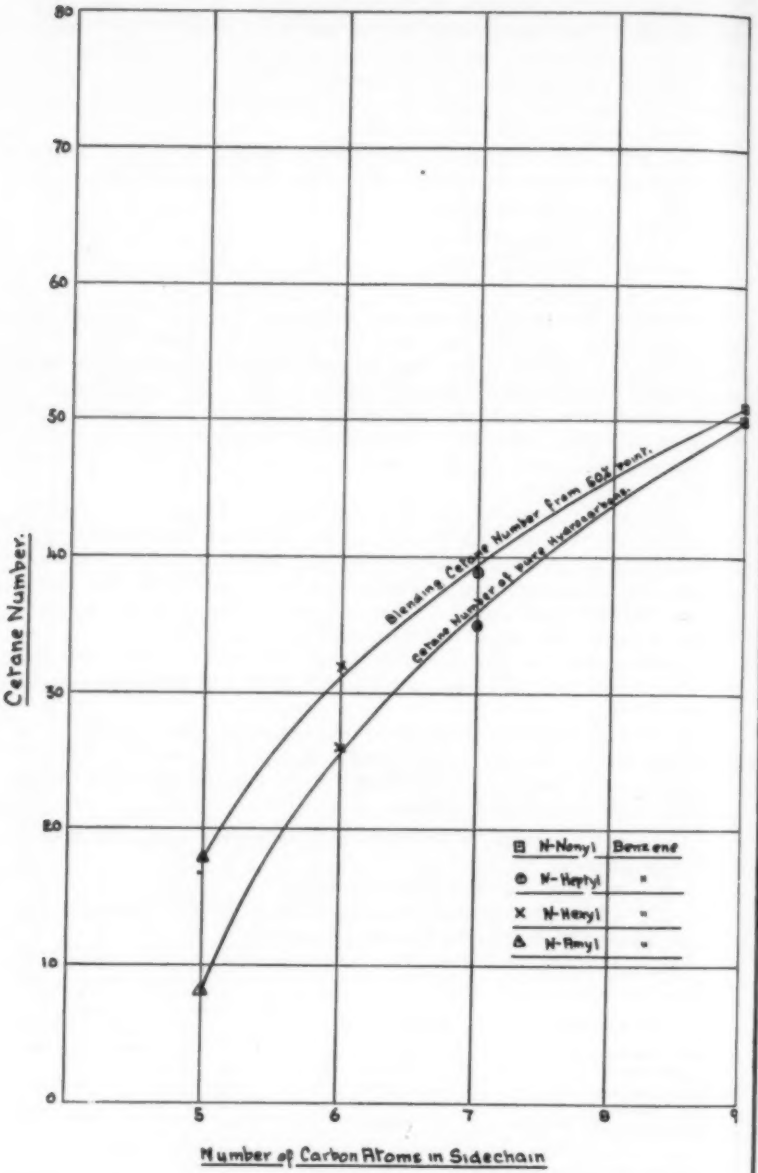

80
70
60
50
40
30
20
10
0
Cetane Number.
5
6
7
8
9
Number of Carbon Atoms in Sidechain
Blending Cetane Number from 60% cont.
Cetane Number of pure Hydrocarbon.
N-Nonyl Benzene
N-Heptyl "
N-Hexyl "
N-Amyl "

FIG. 2.

Kreulen * gave a formula for the calculation of cetene number on the aromatic, naphthenic and paraffin side-chain content as follows :—

$$\text{Cetene number} = -0{\cdot}2A + 0{\cdot}1N + 0{\cdot}85P$$

The calculated figures together with the determined figures are shown in the following table :—

Hydrocarbon.	Calculated cetene number.	Determined cetene number.
n-Amylbenzene . . .	30·3	10
n-Hexylbenzene . . .	35·1	30
n-Heptylbenzene . . .	38·0	40
n-Nonylbenzene . . .	45·4	57

From the above examples it will be noted that there is little agreement between the results as calculated by these two formulæ, and, furthermore, only with the Moore and Kaye formula do the calculated cetene numbers even approximately agree with the experimental determinations.

The authors wish to thank Professor A. W. Nash for his interest and for the facilities he has granted in connection with this work.

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University of Birmingham
and
Esso European Laboratories,
London.

* *J. Instn. Petrol. Tech.*, 1937, **23**, 253.

DISCUSSION.

Mr. R. Stansfield said that the papers read at that session had all been of such high quality that any one of them would have been adequate on which to base a discussion. From the mass of material available he intended to confine his comments to Messrs. Blackwood and Cloud's paper and to that given by Messrs. Broeze and Hinze.

It would be noticed on page 689 of the former paper that a difference between fuel behaviour occurred as the engine speed was altered, low speeds being insensitive to fuel ignition quality, but high speeds demanding a high ignition quality for the best performance.

This examination of the effect of variables such as speed was very important in high-speed diesel fuel and engine research if misleading conclusions were to be avoided.

On reference to the second of the papers referred to, it would be noted that fuel consumptions were shown as improving materially with decrease of ignition quality, but this effect was well known to take place only when an engine was running at or above the smoke-point. Full rated output or overload output was, of course, a very important aspect of engine duty, but no one would contend that any engine was bought to run at its maximum possible load for more than a small fraction of its total life. In fact any discriminating engineer would make every effort to run his engines at loads not exceeding, say, 80 per cent. of maximum rating except for short emergency periods.

When the effect of ignition quality at loads other than peak values was examined, it was found that results somewhat similar to those of Blackwood and Cloud were obtained—*i.e.*, change of load altered the relative importance of ignition quality. As load fell to just below the smoke-point, but still well above the average running load for most engines, the low-ignition fuel no longer had any advantage over that of higher quality, and when low loads of considerable duration in the running life of vehicle engines were encountered, the low-ignition-quality fuels were liable to give late burning (not always definite misfiring), and this was accompanied by fuel consumptions which might reach 20 per cent. excess above fuels of more ready ignitability. Burning of this sort was not detected easily by the attendant, but might provoke a dirty condition of the engine and other troubles. It was assumed when making such comparisons that the fuels were similar in distillation characteristics, for, by special selection of samples, almost any desired comparison might be obtained, regardless of ignition quality.

Reverting again to Messrs. Broeze and Hinze's paper, the scales used for the maximum rate of pressure rise curve and the maximum pressure curve of Fig. 10, for example, suggested at first sight that there was little difference between the two effects. Closer inspection showed, however, that the alteration in maximum pressure when changing from the high to the low cetane fuel was about 13 per cent., whilst the change of rate of pressure rise was as much as 67 per cent. It was the latter alteration which affected smooth running and, often, stresses in engine parts, reducing the safety margin allowed by the engine designer. This stress effect was, further, one which must be considered solely in relation to peak output, and was much more serious than consumption figures at peak output which formed only a small percentage of any engine's life-history.

Mr. E. L. Harland said that when considering the desirable characteristics of oil-engine fuels from a technical point of view, it might be as well to remember that the actual grades supplied to a given area were frequently determined far more by artificial considerations than by technical ones.

One was reminded of two such areas by the references made in the papers to ignition quality, and particularly by Mr. Stansfield's remarks, which stressed that fuel consumption experiments in that connection should be carried out at m.e.p.'s corresponding to those likely under actual operating conditions. The fact was, however, that they had actual knowledge of the behaviour of engines in service using fuels of widely differing ignition quality, and that information was surely at least as valuable as experimental data.

Thus throughout a large area in the Far East, owing to the prohibitive price of any fuel not passing certain customs restrictions, the vast majority of oil engines of all types and speeds had to operate on a special distillate grade which, in qualifying for

tax exemption, was inevitably of very low ignition quality, judged by Western standards. But, as in most cases where no alternative was possible, it was surprising how well the engines behaved on that fuel! Whatever else might be said, high fuel consumption was certainly not a complaint forthcoming from that country. In fact, generally-speaking, remarkably good fuel-consumption results were reported using the low-ignition-quality fuel.

By way of contrast, the other area which he had in mind also provided suppliers with an artificial problem, but the customs test could be and was met in that case by a blended diesel-fuel grade of very high ignition quality, which sold alongside a grade passing the same test but of medium ignition quality. Of the two, the latter fuel was the more favourably received by the industrial engine users, to whom both grades were often available at the same price.

Whether or not the differing ignition quality was in that instance purely incidental to the results obtained was a matter of conjecture. Such an example did, however, serve to demonstrate that high ignition quality did not necessarily mean good all-round service performance. In fact, in the experience of some operators the very opposite appeared to be true.

Mr. P. Draper said that reference had been made in some papers and during the discussion to the relative merits of high- and low-ignition-quality (delay angle) fuels, and some attempt had been made to specify the cetane numbers of fuels suitable for high-speed engines.

It was, of course, known that a high cetane fuel (short delay angle) would give smooth running, less shock on bearings, and easy starting; but this was a matter of degree, and it might not be desirable for a fuel to have a higher cetane number than the minimum on which it could operate satisfactorily, especially if there were other desirable characteristics which went with low cetane fuels.

In this connection the following might be of interest as indicating some of the benefits obtained with low cetane fuels.

As the result of comparative tests in high-speed engines, it had been found that, in general, low cetane distillate fuels kept an engine in a clean condition, that was to say, less carbon was formed in the combustion chamber, which was to be expected from a consideration of the process of burning in a combustion chamber, in which a comparatively long delay period might enable the fuel spray to search out its air before inflammation occurred in the vicinity of the nozzle.*

Other advantages of low cetane fuels included low fuel consumption on a volumetric basis (miles per gallon) and the low pour point and absence of filter troubles referred to by Messrs. Broeze and Hinze.

It might be seen that some of these advantages were not directly attributable to the long delay angle, but nevertheless the fact remained that the crude oils which provided fuels of this type did also possess the other qualities which were desirable.

Mr. L. V. Ward said that Mr. Broeze had pointed out that the reason for research into the possibility of increasing ignition quality by artificial means, at the same time keeping a low pour point, was largely with respect to aviation requirements, since very special conditions in that field of diesel-engine operation had to be met.

The normal diesel-fuel trade in the world was adequately satisfied by fuels which had no need of dope and which, it had been pointed out, gave trouble-free operation in many large areas in the world. In certain papers high ignition quality had been stressed, but he would ask: What was understood by high ignition quality and what was considered low ignition quality? Fuels as they appeared then on the world's market varied widely in ignition quality, and they all had their place in diesel-engine operation. Even high-speed diesel engines such as were used in passenger transport vehicles might be adjusted to give excellent performance on a wide range of distillate fuel. Medium-speed industrial-type engines were even more easily persuaded to consume efficiently a wide range of both distillate and blended fuel, whilst the larger slow-speed engines were quite happy on fuel which might be considered of very low ignition quality.

Specifications were a guide, and extremely necessary where such considerations as

* See Boerlage and Broeze, "*Gas and Oil Power*," January 1935.

hard carbon, sulphur content, ash, etc., were concerned, but ignition quality was one of those qualities of a fuel which, as Mr. Stansfield had stated, showed up to a different extent in different designs of engines, so that it was misleading, and he thought erroneous, to state hard-and-fast limits. C.I. engines and their fuel were complementary to each other, and they must recognize that the scientific development of the former was bound up with the qualities of the available supply of the latter. Let them not mistake ignition quality for fuel quality.

Mr. A. T. Wilford referred to the comments in Messrs. Blackwood and Cloud's paper, regarding the influence of specific gravity on fuel consumption when fuel was purchased on a gallonage basis. This matter was of considerable interest to a large user such as the London Passenger Transport Board, where careful records were kept of the miles per gallon figures obtained and any variations were subjected to close investigations. Such variations were generally found to be due to weather conditions or loadings, or a combination of the two, although at times these factors did not constitute an adequate explanation. Other things being equal, a fuel of the highest possible specific gravity would, of course, be preferred. Bench and road tests had been carried out recently with two fuels of closely similar ignition quality, but differing by 0·01 in respect of specific gravity. The bench tests, which were carried out in two different laboratories, had failed to differentiate between the fuels in respect of consumption in pints per B.H.P.H. The road tests had, however, shown a tendency for the heavier fuel to be slightly the more economical, and it was intended to follow up the matter when circumstances permitted.

He asked for further information as to the ideal fuel. He was given to understand that for some types of engines a fuel of high cetane number was less efficient than one of lower ignition quality, whilst other speakers had indicated that satisfactory results were obtainable from fuels of low cetane number. He also asked for a numerical definition of the terms "low" and "high" cetane numbers, respectively. Finally, in reference to Messrs. Broeze and Hinze's experiments he inquired as to whether there was any prospect of obtaining cheaper fuels by using materials of low ignition quality suitably doped.

Mr. E. L. Harland said that with lower-ignition-quality fuels the user might notice increased knock or roughness and poorer startability, but after that his balance appeared to be loaded on the other side, for he gained on fuel consumption, power, and what might be termed "clean running."

One question he would like to raise in view of a previous contribution to the discussion: were they to assume that references in the various papers to ignition quality applied only where entirely distillate grades of fuel were concerned? He would not have thought this restriction to the principles put forward necessary and, in any case, it should be remembered that, in many countries overseas, the fuels normally predominating for oil-engine operation were grades containing appreciable proportions of undistilled fractions.

Messrs. J. J. Broeze and J. O. Hinze in reply to Mr. Stansfield's comments wrote as follows:

"The remarks made by Mr. R. Stansfield are very interesting and the authors agree to a certain extent with them.

They agree that the differences in specific fuel consumption which are in favour of the low ignition quality fuels, are substantially found at high loads. They do not agree that these differences are restricted to the full- and overload range; numerous tests on high speed engines of several types have shown that in many cases also at lower loads, even beyond the load corresponding with minimum fuel consumption, the low ignition quality fuel may be in favour. It will be put forward that the results given in Fig. 10 of the paper refer to tests carried out at normal running conditions of the engine (b.m.e.p. = 5·3 kg./cm.^{2}). Only at low loads, which, however, are not of importance for high duty Diesel engines, the facts which Mr. Stansfield has mentioned in his remarks may occur.

As to the influence of the ignition quality of the fuel on smooth running and on stresses in engine parts, Mr. Stansfield has pointed out that a closer inspection of Fig. 10 shows that the alteration in maximum pressure when changing over from the

high to the low cetene fuel was about 13 per cent., whereas the change of rate of pressure rise was as much as 67 per cent.

In this respect the authors wish to put forward that the rate of pressure rise is unfortunately still considered as being the predominating factor. This is only partly true. A closer mathematical investigation of the influence of impulsive forces in vibration problems shows that when the time in which maximum load is reached is short with respect to the own period of vibration of the system (shorter than about one-fourth) the amplitude of vibration is only determined by the maximum load, independent of the fact in which way that maximum is reached. This was particularly the case with the engine referred to in Fig. 10; as the compression pressure at which the sudden pressure rise due to combustion started was about 25 atm., the difference between the low ignition quality and the high ignition quality was only 20% in favour of the latter. In fact, when running the engine on both fuels it was hardly possible to observe a difference in smoothness of running."